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Proper Spacing and Depth of Tile Drains Determined by the Physical Properties of the Soil

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PROPER SPACING AND DEPTH OF TILE DRAINS DETERMINED BY THE PHYSICAL PROPERTIES OF THE SOIL[1]

J. H. Neal

INTRODUCTION

The proper spacing and depth of tile lines has long been a perplexing problem. In most cases, for many years the tile drainage systems were installed with a certain spacing and depth because another successful system had been put in with such a spacing and depth. The irrigation engineers have already worked out relationships between soils and amounts of irrigation water to apply, but the drainage engineers, with the exception of the German, have failed to find a satisfactory relationship between the soil and rate of water movement through the soil. Several German drainage engineers, including Breitenback (4) and Rothe (15), have worked out the tile spacing and depth as a function of the hygroscopicity of the soil, but the hygroscopicity is not a readily adaptable index, especially by engineers practicing among the farmers. Since 95 per cent of their lateral tile drains are three inches or less in diameter (15), and since their system of farming is much more intensive than in this country, the German formulas do not fit our conditions.

The writer has made a study of four tile drainage systems in different parts of Minnesota where there is a wide variation in soil type. Altho the tile drainage systems were not installed for experimental purposes, there was a variation in spacing at each of the stations studied and a variation in depth as between the stations. Three of the systems were designed by members of the staff of the division of agricultural engineering, University of Minnesota, and the fourth by a drainage engineer in private practice.

Study of the fluctuation of the ground water table caused by precipitation was made at each of these stations over a period of four years, 1925 to 1928. These studies were largely based on contemporaneous records of the duration and amount of local precipitation secured at or near the drainage areas.

REVIEW OF PREVIOUS INVESTIGATIONS

A summary of spacings and depths of drain tile as recommended by other investigators is given in Table 1. Most of the American investigators give only general recommendations which are not readily

[1] A thesis submitted to the faculty of the Graduate School of the University of Minnesota in partial fulfillment of the requirements for the Degree of Agricultural Engineer, March, 1934.

interpreted by others, while most of the German investigators give some type of formula. The most applicable formulas are given by Rothe (15). For northern Germany he recommends that tile be placed at a depth of 1.25 meters (4.10 feet) and spaced according to the following formula:

$$E = \frac{117}{W} = \frac{638}{W_e}$$

E = spacing in meters. W = hygroscopicity. W_e = per cent washable particles (those under 0.002 mm. diameter).

Table 1

Drain Tile Spacings and Depths Recommended by Other Investigators

Description of soil	H.C.*	Tile spacing, feet	Tile depth, feet	Investigator	State or country
Clay	15.0	26	3-4	Breitenbach	Germany
Clay		60-75	3-3½	Jones	Alabama
Clay	15.0	25	3-4	Rothe	Germany
Clay		33-50	3	Schlick	Iowa
Clay loam	10.0	36	3-4	Breitenbach	Germany
Clay loam		60	3	Lynde	North Carolina
Clay loam	10.0	37	3-4	Rothe	Germany
Average loam	5.0	53	4	Breitenbach	Germany
Average loam	5.0	72	4	Rothe	Germany
Average loam		75-100	4	Schlick	Iowa
Fine sandy loam		100-125	3½	Lynde	North Carolina
Sandy loam		120	3½	Bartel	North Carolina
Sandy loam		100-120	4	Schlick	Iowa
Sloughs		600†		Minder	Minnesota

* Hygroscopicity taken from graphs (15, Figure 54).
† Additional tile lines to be laid at locations and depths indicated by crop conditions.

Rothe's formulas give much closer spacings than those recommended by most American drainage engineers, but when one considers that the Germans practice a much more intensive agriculture than is usually found in America and that 95 per cent of their lateral tile drains are 8 cm. (3 in.) or less, one can account for the closer spacings. The annual precipitation in Germany is not much higher than that in Minnesota, but a much greater percentage falls in the winter than is the case in Minnesota.

In summing up the conclusions presented by the different investigators mentioned, it is pointed out that in most cases they indicate more or less directly that the proper tile drainage design is a function of some physical property of the soil, such as hygroscopicity, permeability, or effective diameter of soil particles. Minder (10) and Razansky (14) seem to see the problem from a practical viewpoint, but neither offers an acceptable solution applicable to all cases. The writer is in accord with the idea presented by Rothe, that, notwithstanding the fact that laboratory tests do not take into account the stratification of the soil or its non-uniformity, such tests give more accurate means of determining the proper depth and spacing than does a mere guess.

Comparatively few soils in need of underdrainage are homogeneous enough in texture to warrant a mathematical design from the results of a few soil analyses. Since a large number of samples should be analyzed before a design is formulated, the method of analysis used should be simple and convenient. In all these cases, the methods presented for making the physical analysis of the soil are too cumbersome for the rural engineer to utilize in practice.

It is the opinion of the writer that the ultimate tile drainage design must be based on both soil characteristics and crop type, but the inadequacy of the data prevent a detailed discussion of the influence of crop type.

The writer has developed a method of design of tile drainage systems based on soil characteristics and constants so simple and effective that it is readily applicable by the rural engineer.

TILE DRAINAGE SYSTEMS STUDIED

The location of each of the four tile drainage systems is shown in Figure 1.

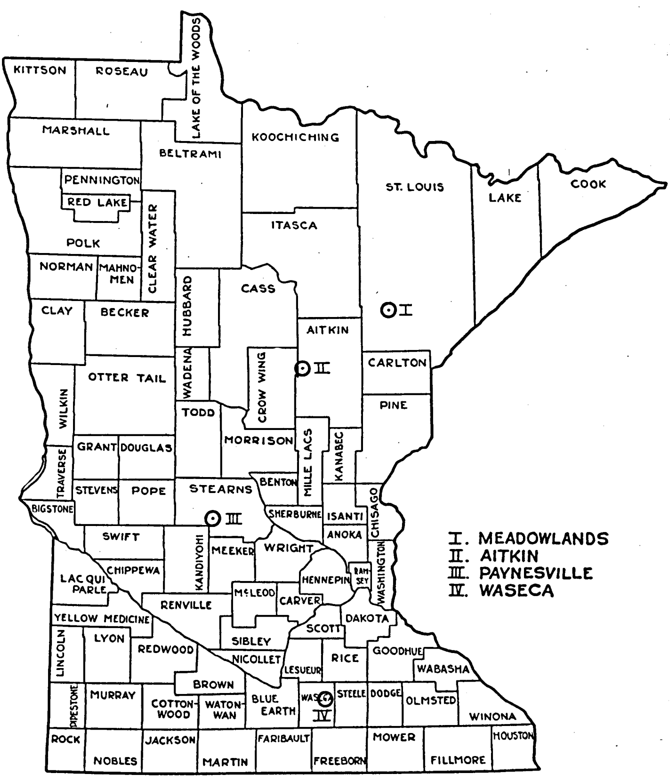

Fig. 1. Location of the Drainage Stations Included in This Study

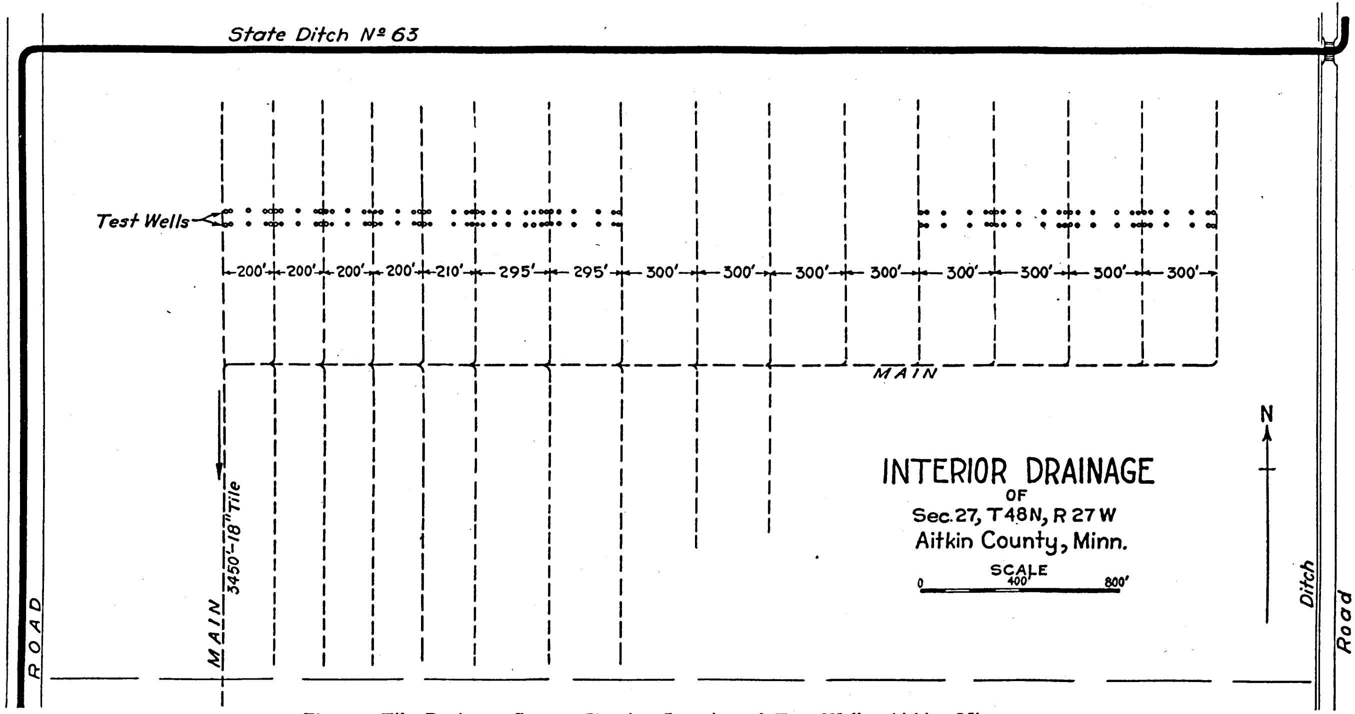

Fig. 2. Tile Drainage System Showing Location of Test Wells, Aitkin, Minnesota

The Aitkin station is in the west central part of Aitkin County, Minnesota, in the bed of old glacial Lake Aitkin and 7 miles northwest of the village of Aitkin. The topography is very flat and the natural drainage poor. There are dredged outlet ditches, both north and south, every one to two miles apart. The tile drainage system studied was originally laid out with parallel lines every 600 or 800 feet apart, but later intermediate lines were put in with spacings of only 200 or 300 feet. The tile-drained tract is a mile long east and west and one-half mile wide north and south, with open ditches along the north and west sides. (See Fig. 2.)

The system was designed for a ¼-inch run-off in 24 hours. The main below the last lateral was 18- and 20-inch tile on a gradient of 0.10 per cent. It was necessary to run the main parallel to the open ditch for 2,650 feet in order to get a suitable outlet. Even then it was impossible to place all the tile lines as deep as they should be for the type of soil. (See page 54.)

The Meadowlands station is in St. Louis County, Minnesota, in the bed of old glacial Lake Duluth, 40 miles northwest of the city of Duluth. The tract includes 7.5 acres in the watershed lying along the Whiteface River. The topography is flat with a gentle slope toward the river, except the last few hundred feet which have been built up by the river, thus forming a basin. The drainage system is laid out in parallel lines ranging from 60 to 135 feet apart. (See Fig. 3.)

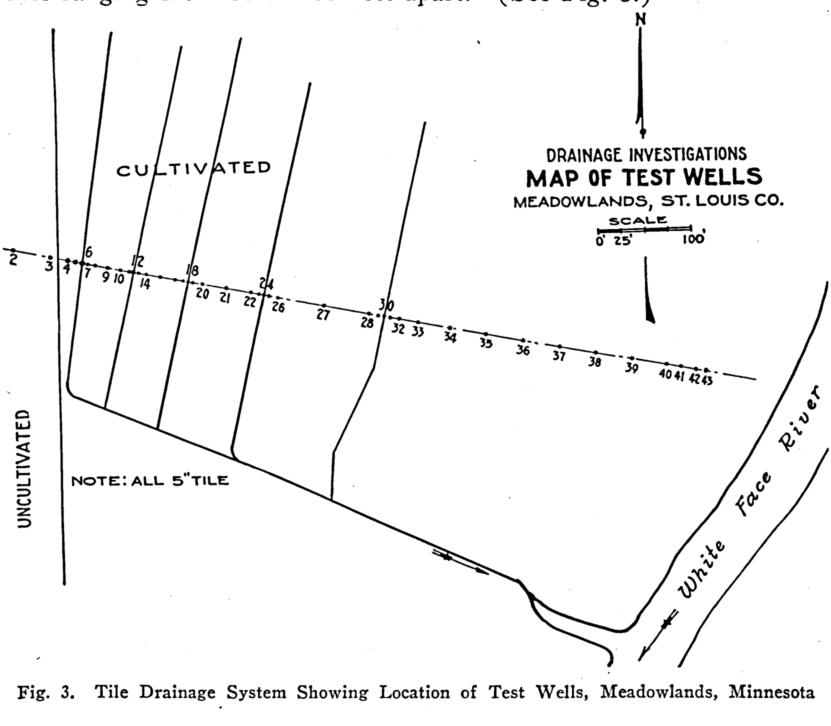

Fig. 3. Tile Drainage System Showing Location of Test Wells, Meadowlands, Minnesota

The main is a 5-inch tile laid with a gradient of 2.00 per cent and designed to carry a 1.25-inch run-off in 24 hours, based on the Chezy-Kutter formula when n = 0.013. Twice in September, 1925, the maximum rate of run-off was greater than 1.25 inches, the greatest being 1.60 inches. All the run-off except deep seepage passes through the tile system.

The Paynesville station is in the south central part of Stearns County, Minnesota, about 5 miles north of Paynesville, in the till plain area. The topography is gently rolling, including many swales and pockets and one small lake bed of about 30 acres. The total watershed includes 208 acres. The ground water observations were made in the lake bed. (See Fig. 4.) With the exception of the old lake bed, the tile lines generally follow the natural depressions. In the lake bed part of the lines are parallel.

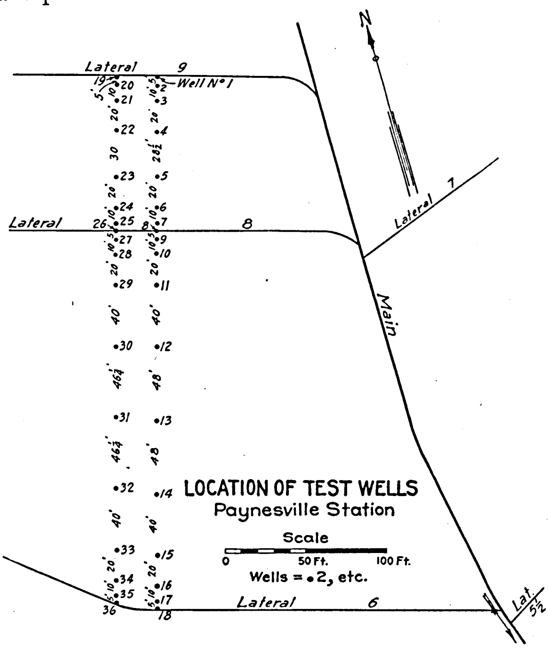

Fig. 4. Location of Test Wells at Paynesville, Minnesota

The lower end of the main is of 16-inch tile laid on a gradient of 0.12 per cent. It is designed to take care of a ½-inch run-off in 24 hours, since all the run-off must pass through the tile. Surface inlets are provided in the depressions in the surface to take care of the flood waters. (See Fig. 5.) Only once (September 17, 1926) during the four years' study did the tile system discharge at its designed capacity. (See Table 11.)

The Waseca station is at the Southeast Experimental Farm near Waseca, Minnesota, toward the southeast corner of the great till plain area. The topography is gently rolling. Part of the tile lines are parallel and part follow the natural depressions. The ground water observations were made on a small portion of the drainage system, including about seven acres in the watershed. The total area of watershed includes 50 acres. A 9-inch tile would carry a ¼-inch run-off in 24 hours, but since 9 inches is not a standard size, a 10-inch tile was used. The gradients are 0.20 and 0.30 per cent, giving a capacity of ⅜-inch run-off in 24 hours. The submain from the 7-acre watershed is a 6-inch tile on a gradient of 0.04 per cent with a capacity of ⅜-inch run-off in 24 hours. The parallel lateral drains are 5-inch tile. (See Fig. 6.)

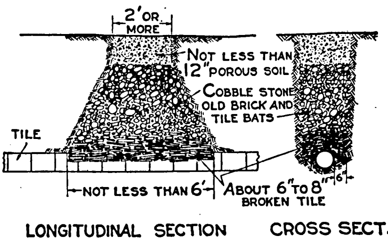

Fig. 5. Section Views of a Surface Inlet to a Tile Drain Designed to Carry Flood Water from a Cultivated Field

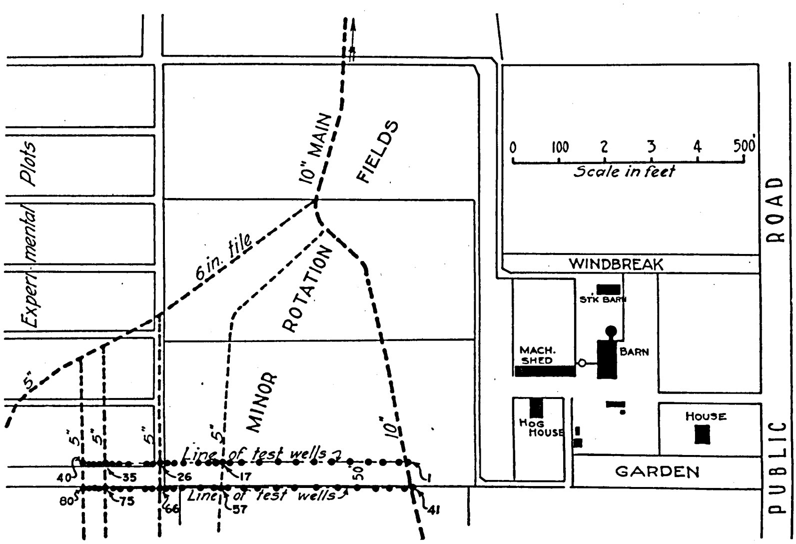

Fig. 6. Location of Test Wells at Waseca, Minnesota

SOIL TYPES

Aitkin

The Aitkin soil is a shallow, well-decomposed woody peat overlying a yellowish gray to gray sand or very sandy loam. Strata of yellowish gray sand of variable thickness occur below the second foot. The peat averages one foot in depth on the east half and 2 feet on the west half of the experimental tract. The tile drainage system on the east half is hereafter referred to as Aitkin-E or Aitkin-Series A, and that on the west half as Aitkin-W or Aitkin-Series B.

Meadowlands

The surface 6 inches of the Meadowlands soil is a light brown, silty clay loam, and the second 6 inches and the second and third feet are gray silty loam containing less organic matter. Occasional clay layers occur in the second, third, and fourth feet.

Paynesville

The Paynesville soil varies from a muck 6 inches in depth to a well-decomposed peat 2 feet in depth. A stratum of mucky clay from 6 to 12 inches in depth underlies the surface muck or peat. The thicker part of this stratum is under the deeper peat. A grayish loam underlies the mucky clay to a depth of more than 4 feet from the surface.

Waseca

The Waseca soil is a silt loam, the surface being a light brown, "heavy" silt loam, while the subsoil, below 4 feet, consists of the unmodified gray boulder clay.

PHYSICAL CHARACTERISTICS OF THE SOIL RELATED TO DRAINAGE

Moisture equivalent.—The moisture equivalents of a large number of samples from each field were determined in duplicate. A few of these are reported in Table 2. All moisture data refer to moisture-free soil. The values range from 3 to 43 in the mineral soils, and from 59 to 325 in the mucks and peats.

Table 2
Moisture Equivalents*

Depth of sample, feet	Aitkin				Meadowlands			Paynesville		Waseca	
	Spacings of:				Spacings of:			Spacings of:		Spacings of:	
	200 feet	295 feet	600 feet	800 feet	60 feet	90 feet	135 feet	100 feet	250 feet	45 feet	125 feet
0-1	120.0	235.0	55.0	235.0	35.2	32.6	36.8	153.7	35.9	37.2	34.4
1-2	7.3	13.5	10.0	13.5	26.2	26.7	28.8	71.3	21.1	35.8	32.7
2-3	11.6	7.9	16.6	7.9	26.3	25.0	20.2	19.8	21.5	34.3	28.0
3-4	15.7	7.3	6.4	7.3	27.0	30.0	25.6	21.9	21.2	26.9	27.9

* Each item is an average of 2 or 3 samples with the exception of those for Aitkin which are single samples.

Pore space.—The total pore space was determined from the volume of water held by the soil when all the pores were filled (11). It is the same as the percentage of water in a saturated soil, expressed on a volume basis. In the mineral soils the pore space shows a fairly uniform increase as the value for the moisture equivalent increases. (See Fig. 7.) The average increase bears a straight line relationship to the moisture equivalent with a slope of 0.7. The following equation expressing this relationship was obtained by the method of least squares:

$$Y = 27.0 + 0.7X$$

Y = pore space expressed as a per cent of the total volume, and
X = moisture equivalent.

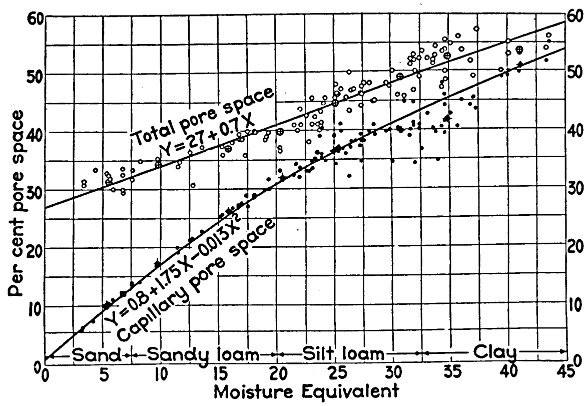

Fig. 7. Pore Space of Soils

The maximum capillary pore space for mineral soils with a moisture equivalent above 15, as determined by the writer (11), is approximately equal to the moisture equivalent. Other investigators including Alway, Harding, Israelson, and Shaw have also determined the capillary capacity of the fine-textured soils to be approximately equal to the moisture equivalent. From 3.0 to 6.5 inches depth of capillary water can be held in each foot of depth of soil. **This water cannot be removed by drainage and about two-thirds of it is available to plants.**

In the muck and peat soils the pore space is not a direct function of the moisture equivalent. Usually, the higher the organic matter content, the greater is the amount of pore space.

Soil plasticity.—In most cases, in practice it is neither convenient nor possible to determine the moisture equivalent of the soil. On this account the writer has worked out a relationship between the moisture equivalent and the upper and lower plastic limits of the soil. The plastic limits were determined according to the Atterberg Method

(2). Atterberg recognized six consistency forms, of which only two are of service in this discussion. These two are as follows:

(a) The tough-flowing consistency: This form is recognized by its thick paste-like consistency. The **upper plastic limit** is the wetness just at which the soil, in layers 1.5 cm. (5/8 inch) thick, ceases to show a tendency to flow. A V-shaped furrow in a cake of soil in a dish will just exhibit flowing by closing at the bottom when assisted by violent jarring. If the soil is too wet, which will be indicated by the complete closing of the furrow when assisted by violent jarring, add more dry soil and thoroly mix. When the proper moisture condition is reached, weigh the wet soil, thoroly dry in an oven at 100° C. (212° F.) and then weigh the dry soil. The difference in weight thus obtained divided by the weight of the dry soil is the **upper plastic limit.**

(b) The plastic consistency: This consistency is recognized by the ability of the soil to be rolled out into a wire. The **lower plastic limit** is the wetness at which the soil can barely be rolled into a wire under the fingers. At this lower limit, when the size of the wire is about the same as that of a lead in a pencil, it will break into segments about 1/8-inch long. To obtain the lower plastic limit, take about 100 grams (4 ounces) of air-dry soil and add water until the soil can be rolled out into a wire as before described. If too much water is added, add more dry soil. When the proper moisture condition is reached, weigh the moist soil, thoroly dry it in an oven at 100° C. (212° F.), and then weigh the dry soil. The difference in weight thus obtained divided by the weight of dry soil is the **lower plastic limit.** The difference between the two consistencies described is the plastic number.

The writer found the average lower plastic limit to be 70 per cent and the average upper plastic limit to be 120 per cent of the moisture equivalent in the case of 49 subsoils. The standard deviations are 8.5 per cent and 11.3 per cent, respectively, while the coefficients of variation are 12 per cent and 9 per cent, respectively. (See Table 3.)

Table 3
Soil Plasticity and Clay Content of Mineral Subsoils

Moisture equivalent		Frequency	Plastic number	Plastic limits				Clay content	
				Lower		Upper			
Range	Average mid-point			Value	% of M. Eq.	Value	% of M. Eq.	Per cent	Ratio to M. Eq.
37.5-42.4	40.4	1	28.7	23.3	58	52.0	129	59.6	1.47
32.5-37.4	34.7	7	20.3	21.5	62	42.0	121	45.8	1.32
27.5-32.4	29.0	13	14.8	21.1	73	35.9	124	37.7	1.30
22.5-27.4	25.3	19	12.6	18.2	72	30.6	121	33.6	1.33
17.5-22.4	20.8	9	10.2	14.3	69	24.3	117	23.3	1.12
12.5-17.4	14.8	10	...	...	..	...	...	14.6	0.99
7.5-12.4	10.0	15	...	...	..	...	...	11.7	1.17
2.5- 7.4	5.6	16	...	...	..	...	...	7.8	1.40
Average (mean)					70		120		1.25
Standard deviation (σ)					8		11		0.26
Coefficient of variation (V)					12		9		.22

Clay content of soils.—Since it is impossible to determine the plasticity of sandy soils, the clay content is used as a substitute for the moisture equivalent in determining the drainage requirements. The clay content was determined by the hydrometer method as described by Bouyoucous (5).

"The final procedure as developed up to date for making mechanical analysis of soils by the hydrometer method is as follows: Add 50 grams of the fine-textured soils or 100 grams of the sand, based on oven-dry conditions, to the dispersing cup. Fill the cup with distilled water to about 1½ inches from the top. Add to the contents 5 cc. of a solution of saturated and filtered sodium oxalate and 5 cc. normal (solution of) sodium hydroxide. If the soil is in lumps, sufficient time must be given for it to slake and to soak. As a matter of fact, it is well to allow all soils to soak for about 15 minutes before dispersing them. The soils should always be air-dry, because in the wet condition they do not slake. The soaking can be done in a separate vessel and the material then washed into the cup. Then connect the cup to the stirring motor, and stir the contents for 5 minutes in the case of sands, and 10 minutes in the case of all other soils. Those soils, however, which are recognized as difficult of dispersion should be dispersed for 20 to 30 minutes, or longer. The sands should not be stirred more than 5 minutes because they seem to undergo grinding.

"Pour and wash the contents into the special cylinder. If 50 grams of soil are used, fill the cylinder up to the lower mark with the hydrometer in it. If 100 grams of soil are used, fill it to the upper mark with the hydrometer in it. Only distilled water should be used. Then take the hydrometer out, place the palm of one hand on the mouth of the cylinder and shake the contents vigorously, turning the cylinder upside down and back several times. Place the cylinder quickly on the table and note the time immediately. Then at the desired period put the hydrometer in the suspension column, record the reading, and then take it out again. There is a tendency for slight amounts of soil material to settle on the shoulder of the hydrometer, and it is better not to leave it in continuously for all readings. Each time the hydrometer is used it should be cleaned.

"At every hydrometer reading the temperature of the suspension should be measured. Great care must be taken, however, not to disturb too much the suspension column in putting in and taking out the hydrometer and the thermometer. For every 1° F. above or below 67° F. apply a temperature correction of 0.2 graduation on the hydrometer. . . . For temperatures above 67° F. the corresponding amount of correction is added to the hydrometer reading, and for temperatures below 67° F. the corresponding amount is subtracted. The corrected hydrometer reading, which represents grams per liter of water, is then divided by the weight of soil taken and multiplied by 100, the result being the percentage of material still in suspension. . . . The corrected hydrometer reading at the end of one hour is divided by the amount (weight) of soil sample and multiplied by 100. The result is percentage of material still in suspension and is considered to be the conventional clay (0.005-000 mm.)."

In the case of 90 subsoils, the writer found that the clay content is equal approximately to the upper plastic limit, being 1.25 times the moisture equivalent. (See Table 3.) The relationship between the moisture equivalent and the clay-plus-silt content of the soil is not very consistent.

Amount of water required to bring the soil to different stages of moistness.—The curves showing the amount of rain required to bring the moisture content of the mineral soils up to the computed hygroscopic coefficient and to the moisture equivalent are parabolas, which tend to flatten out when the moisture equivalent rises above 15. The graph showing the amount of rain required to fill all the pore spaces of the soils is a straight line. (See Fig. 8.)

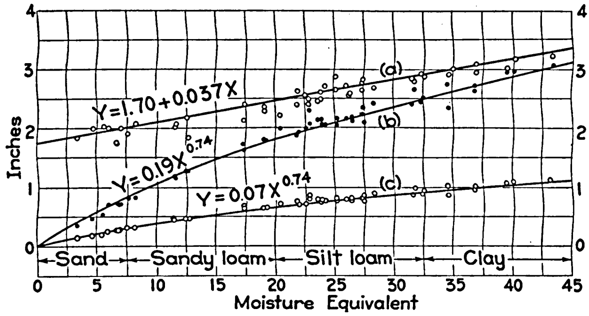

Fig. 8. The Amount of Rainfall that Six-Inch Layers of Moisture-Free Soils Would Require to Bring Their Moistness to: (a) Complete Saturation, (b) The Moisture Equivalent, (c) The Hygroscopic Coefficient

The total amount of water in the first foot and in the first four feet of soil, when the moisture content is at the moisture equivalent, has been calculated and is as follows for each of the four stations:

	First foot	First 4 feet
Aitkin	4.3 inches	9.6 inches
Meadowlands	4.1 inches	12.3 inches
Paynesville	2.7 inches	10.4 inches
Waseca	5.0 inches	14.4 inches

The water-holding capacity of the soil has a definite relationship to the disposal of the precipitation and a definite influence in determining the drainage requirements of these soils, as will be shown more clearly.

PRECIPITATION

The precipitation records used in this study for the Aitkin Station were those of the U. S. Weather Bureau Station at Sandy Lake Dam, about twenty-five miles northeast of the experimental tract, and those taken by a local observer in Aitkin, about seven miles southeast.

The records at Meadowlands and Waseca were taken by co-operative observers of the U. S. Weather Bureau, the stations being about a mile from the respective experimental drainage stations. The records were taken at 6:00 p.m. every day. The Meadowlands Station was started in 1916; the one at Waseca in 1914.

The records at Paynesville were taken at 7:00 a.m. and 7:00 p.m. by a local observer on the farm containing the experimental tract throughout the period during which the drainage studies were made. The time of the storms was recorded in the same manner as by the co-operative observers of the U. S. Weather Bureau. The records for St. Cloud, about thirty miles northeast, are also included in the study to get the normal and the maximum precipitation for the region.

The monthly precipitation for each of the stations and annual deviations from the normal are given in Table 4.

Table 4
Monthly Precipitation

Month	Aitkin* 1925	Aitkin* 1926	Aitkin* 1927	Aitkin* 1928	Aitkin* Normal	Meadowlands 1925	Meadowlands 1926	Meadowlands 1927	Meadowlands 1928	Meadowlands Normal
	inches	inches	inches	inches	inches	inches	inches	inches	inches	inches
January	0.39	0.69	0.76	0.30	0.73	0.31	0.49	0.70	0.52	0.61
February	1.02	0.62	0.88	0.24	0.60	0.71	0.78	1.44	0.25	0.94
March	0.50	1.13	1.07	0.52	1.13	0.47	2.22	1.72	0.30	1.20
April	1.71	0.05	0.66	1.38	2.00	0.89	0.46	1.94	1.78	1.72
May	1.39	1.25	1.07	1.52	3.13	1.13	2.60	2.46	0.55	2.81
June	4.38	2.47	3.24	3.89	3.82	3.91	2.62	2.57	5.37	3.57
July	3.49	2.97	3.33	5.47	3.92	3.46	1.95	2.66	5.79	3.14
August	5.23	4.52	3.14	4.23	3.57	3.49	3.87	2.42	5.34	3.30
September	3.57	5.15	1.76	5.80	2.84	6.10	4.27	1.67	3.77	3.41
October	0.57	1.51	1.55	3.12	1.98	1.27	2.08	1.66	3.87	1.62
November	0.48	0.80	0.94	0.22	1.15	0.51	1.59	2.09	0.28	0.84
December	0.28	0.79	0.94	0.81	0.72	1.10	0.83	1.29	0.67	0.92
Total	23.01	21.95	19.34	27.50	25.59	23.35	23.76	22.62	28.49	24.08
Deviation from normal	−2.58	−3.54	−6.25	+1.91	....	−0.73	−0.32	−1.46	+4.41	....
Total, March to October	20.84	19.05	15.82	25.93	22.39	20.72	20.07	17.10	26.77	20.77
Deviation from normal	−1.55	−3.34	−6.57	+3.54	....	−0.05	−0.70	−3.67	+6.00	....

Month	Paynesville 1925	Paynesville 1926	Paynesville 1927	Paynesville 1928	Paynesville Normal	Waseca 1925	Waseca 1926	Waseca 1927	Waseca 1928	Waseca Normal
January	0.39	0.84	0.29	0.29	0.82	0.55	0.55	0.84	0.10	0.80
February	0.37	0.40	0.25	0.71	0.66	0.25	0.35	0.65	1.61	1.09
March	0.34	1.03	1.76	0.64	1.25	0.35	0.55	2.32	0.56	1.52
April	2.16	0.29	3.54	1.53	2.26	1.84	1.42	2.34	4.18	2.33
May	1.07	0.82	3.31	0.87	3.59	0.79	3.44	3.30	3.23	3.77
June	4.96	4.87	2.59	3.35	4.51	8.84	2.41	4.08	2.97	4.64
July	5.07	4.07	4.14	5.20	3.85	5.79	2.17	0.84	1.37	3.73
August	1.84	5.32	2.34	4.55	3.28	0.48	2.59	1.10	8.90	3.66
September	1.81	9.28	1.58	3.18	3.36	5.72	8.22	7.20	1.39	3.58
October	0.43	1.20	1.73	2.15	2.18	1.34	1.16	1.56	2.07	1.57
November	0.96	1.38	1.30	0.81	1.19	0.29	1.55	1.26	0.67	1.10
December	0.42	0.41	1.93	0.71	0.51	0.73	1.93	0.62	0.39	0.69
Total	19.82	29.91	24.76	23.99	27.46	26.97	26.34	26.11	27.44	28.48
Deviation from normal	−7.64	+2.45	−2.70	−3.47	....	−1.51	−2.14	−2.37	−1.04	....
Total, March to October	17.68	26.88	20.99	21.47	24.28	25.15	21.96	22.74	24.67	24.80
Deviation from normal	−6.60	+2.60	−3.29	−2.81	....	+0.35	−2.84	−2.06	−0.11	....

* Sandy Lake Dam.

In the latitude of Minnesota the winter precipitation has very little effect upon the local ground water table, since the snow melts and runs off before the ground thaws in the spring. Practically all precipitation falling between November 1 and March 1 is snow and can be disregarded as far as the design of a tile drainage system is concerned. The precipitation for the four winter months is low, averaging less than one inch per month. The precipitation for March and April may be either snow or rain. Frequently the precipitation for March also runs off while the ground is still frozen. The average normal annual precipitation for the four stations is 26.40 inches, while the average normal for the spring, summer, and fall or the farming season is 23.06 inches.

In all cases there was one month or more during the growing season of each year in which the precipitation was below normal. With the exception of 1927, there was also one month or more each year in which the precipitation was above normal. In general the periods of excess precipitation were shorter than those of deficient precipitation.

A summary of the periods and amounts of deficient or excess precipitation are given in Table 5.

Table 5

Summary of the Periods and Amounts of Deficient or Excess Precipitation

Year	Station	Periods and amounts of deficient or excess precipitation				Condition for the year	
		Deficiency	Inches	Excess	Inches	Deficiency, in.	Excess, in.
1925	Aitkin	March to May, incl., July	3.09	June, Aug., Sept.	2.95	2.58	...
*	Meadowlands	Jan. to May, incl.	3.77	June to Sept., incl.	3.54	0.73	...
	Paynesville	Jan. to May, incl.	4.25	June, July	1.67	7.64	...
		Aug. to Oct., incl.	4.74				
†	Waseca	Jan. to May, incl., Aug.	8.89	June, July, Sept.	8.40	1.51	...
1926	Aitkin	April to July, incl.	6.13	Aug., Sept.	3.26	3.54	...
*	Meadowlands	April to July, incl.	3.61	Aug. to Nov., incl.	2.64	0.32	...
	Paynesville	Feb. to May, incl.	5.22	June to Sept., incl. (Sept. 3 times the normal)	8.54	...	2.45
†	Waseca	Jan. to Aug., incl.	8.06	Sept.	4.64	2.14	...
1927	Aitkin	March to Nov., incl.	6.50		...	6.25	...
*	Meadowlands	May to Sept.	4.45		...	1.46	...
	Paynesville	May, June, Aug. to Oct., incl.	5.37	March, April, July	2.07	2.70	...
†	Waseca	July, Aug.	5.45	March, Sept.	4.42	2.37	...
1928	Aitkin	Jan. to May, incl.	3.63	June to Oct., incl.	6.38	...	1.91
*	Meadowlands	Jan. to March, incl., May	3.94	June to Sept., incl.	9.10	...	4.41
	Paynesville	March to June, incl.	5.22	July, Aug.	2.62	3.47	...
†	Waseca	June, July	4.03	April, Aug., Oct.	7.59	1.04	...

* The distribution and intensity at Meadowlands corresponded very closely to that at Aitkin.
† See the special discussion of heavy storms at Waseca on page 22.

Precipitation Periods

In this study only the storm periods between March 1 and October 31 for the years 1925 through 1928 were included. During this period 114, 127, 94, and 129 storm periods occurred, respectively, at Aitkin,

Table 6
Summary of Precipitation
1925-28, inclusive

	Rains occurring March 1–October 31, inclusive									
	Aitkin		Meadowlands		Paynesville		Waseca		Total	
	No.	Per cent	No.	Per cent	No.	Per cent	No.	Per cent	No.	Per cent
Total number of rains 0.10 inch or more	114	100.0	127	100.0	94	100.0	129	100.0	464	100.0
Rains of 0.10 to 0.99 inch	93	81.7	108	85.0	73	77.7	105	81.5	379	81.7
When less than 3 inches fell in previous 30 days	60	52.7	74	58.2	50	53.2	73	56.7	257	55.4
(A) and less than 1 inch fell in previous 7 days	56	49.2	69	54.3	46	48.9	67	52.1	238	51.3
(B) and 1 inch or more fell in previous 7 days	4	3.5	5	3.9	4	4.3	6	4.6	19	4.1
When 3 inches or more fell in previous 30 days	33	29.0	34	26.8	23	24.5	32	24.8	122	26.3
(A) and less than 1 inch fell in previous 7 days	20	17.6	17	13.4	17	18.1	21	16.3	75	16.2
(B) and 1 inch or more fell in previous 7 days	13	11.4	17	13.4	6	6.4	11	8.5	47	10.1
Rains of 1.00 to 1.99 inches	14	12.2	13	10.2	16	17.0	14	10.8	57	12.3
When less than 3 inches fell in previous 30 days	7	6.1	5	3.9	10	10.6	7	5.4	29	6.3
(A) and less than 1 inch fell in previous 7 days	6	5.2	5	3.9	8	8.5	5	3.9	24	5.2
(B) and 1 inch or more fell in previous 7 days	1	0.9	0	0.0	2	2.1	2	1.5	5	1.1
When 3 inches or more fell in previous 30 days	7	6.1	8	6.3	6	6.4	7	5.4	28	6.0
(A) and less than 1 inch fell in previous 7 days	5	4.4	6	4.7	4	4.3	2	1.5	17	3.6
(B) and 1 inch or more fell in previous 7 days	2	1.7	2	1.6	2	2.1	5	3.9	11	2.4
Rains of 2 inches or more	7	6.1	6	4.8	5	5.3	10	7.7	28	6.0
When 3 inches or more fell in previous 30 days	4	3.5	3	2.4	1	1.0	4	3.1	12	2.6
(A) and less than 1 inch fell in previous 7 days	4	3.5	2	1.6	1	1.0	4	3.1	11	2.4
(B) and 1 inch or more fell in previous 7 days	0	0.0	1	0.8	0	0.0	0	0.0	1	0.2
When 3 inches or more fell in previous 30 days	3	2.6	3	2.4	4	4.3	6	4.6	16	3.4
(A) and less than 1 inch fell in previous 7 days	3	2.6	2	1.6	4	4.3	4	3.1	13	2.8
(B) and 1 inch or more fell in previous 7 days	0	0.0	1	0.8	0	0.0	2	1.5	3	0.6

Table 7
Intensity of Precipitation
1925-28

Item	Aitkin		Meadowlands		Paynesville		Waseca		Total	
	Inches	Per cent of total rainfall	Inches	Per cent of total rainfall	Inches	Per cent of total rainfall	Inches	Per cent of total rainfall	Inches	Per cent of total rainfall
March 1 to October 31, inclusive										
Total precipitation	79.66	100	83.75	100	72.02	100	94.67	100	330.10	100
Rains of 0.10 to 0.99 inch	38.33	48	47.38	56	29.37	41	43.35	46	158.43	48
Rains of 1.00 to 1.99 inches	18.65	23	17.66	21	22.33	31	19.19	20	77.83	24
Rains or 2.00 or more inches	18.18	23	15.50	19	14.99	21	29.20	31	77.87	24
May 1 to August 31, inclusive										
Total precipitation	51.65	100	49.63	100	36.56	100	52.30	100	190.14	100
Rains of 0.10 to 0.99 inch	23.66	46	25.25	51	9.95	27	24.55	47	83.41	44
Rains of 1.00 to 1.99 inches	13.09	25	10.70	22	15.77	43	10.87	21	50.43	27
Rains of 2.00 or more inches	13.00	25	12.70	26	8.52	23	15.12	29	49.34	26

Meadowlands, Paynesville, and Waseca, during which more than 0.10 inch of rain fell. The storm periods lasted from a few minutes to nine days. If precipitation fell every day for several days, the whole period was considered as one storm even tho it did not rain continuously for the whole time.

The rains were grouped into those of less than 1.00 inch, 1.00 to 1.99 inches, and 2.00 inches or more, and classified according to the amount of precipitation that fell in the previous 7- and 30-day periods.

The distribution as to intensity of these rains and as to previous precipitation is shown clearly for each station in Table 6.

The magnitude of the rain storms is given in Table 7. About half of the precipitation comes in rains of less than one inch, one fourth in rains of 1.00 to 1.99 inches, and one fourth in rains of 2.00 inches or more. The larger rains occur for the most part during the summer months.

In general the big rains, those of 2.00 inches or more, occur when there has been less than one inch during the previous 7 days. During the 4-year period of this investigation, there was a total of 28 rains of 2.00 inches or more at the 4 stations, 24 of these coming when there had been less than one inch of rain during the previous 7 days. About half of the big rains occurred when there had been less than 3 inches in the previous 30 days and half when there had been 3 inches or more in the previous 30 days. This was true not only for the 4-year period of this investigation but also for the 10-year period preceding. (See Table 8.) There were 23 rains of 2.00 inches or more during this 10-year period, of which 16 were preceded by less than one inch of rain in the previous 7 days.

Altho the 4-year period of this investigation was one of deficient rainfall, the precipitation being above normal in only one year out of the four for each of the stations at Aitkin, Meadowlands, and Paynesville, and below normal for all four years at Waseca, nevertheless more large rains occurred than in the preceding 10-year period. At Aitkin the largest rain between 1914 and 1928 occurred on August 29, 1925, when 3.80 inches fell in one day. Only 0.12 of an inch of rain had fallen in the previous 7 days. The largest 24-hour precipitation on record at Meadowlands and also at Waseca occurred during this 4-year period. At Meadowlands the largest 24-hour storm on record (for a period of 12 years) was that of September 6, 1925, when 2.80 inches fell in 9 hours, while the greatest storm period was from June 25 to 28, 1920, when 1.05, 0.85, 2.25, and 0.48 inches fell on the respective days, the next largest being June 15 to 23, 1928, when 4.05 inches fell, ranging from a trace to 1.30 inches in one day. (See Table 10 for the amount of precipitation during the previous 7- and 30-day periods.)

Table 8
Storm Periods When Two Inches or More of Rainfall Occurred in 24 Hours 1915-24, inclusive

Date of storm	Date of maximum rainfall	Maximum 24-hour rainfall	Rainfall during storm	Amount of rainfall in previous 7 days	Amount of rainfall in previous 30 days
		inches	inches	inches	inches
		Aitkin (Sandy Lake Dam)			
May 15-17, 1915	15	2.18	2.57	0.04	1.45
July 14, 1915	14	2.69	2.69	0.00	3.52
July 28-30, 1919	29	2.00	2.48	0.50	2.37
August 2, 1919	2	2.00	2.00	2.48	4.30
June 25-27, 1920	26	2.05	3.80	0.30	5.66
July 14, 1922	14	2.50	2.50	0.18	0.88
July 9, 1923	9	2.40	2.40	1.00	4.43
July 20-22, 1924	20	2.10	2.50	0.00	2.68
		Meadowlands			
June 25-28, 1920	27	2.25	4.63	0.70	6.66
		Paynesville			
May 21-23, 1916	21	2.00	2.81	1.72	1.73
June 29, 1916	29	2.00	2.00	1.60	4.08
May 10-11, 1920	10	2.00	3.05	0.00	1.44
June 25-28, 1920	27	3.25	4.49	0.00	6.53
September 13-16, 1921	13	2.15	3.68	0.57	*
June 22-24, 1923	24	2.35	2.83	0.96	2.34
		Waseca			
July 17-18, 1915	18	2.70	2.77	2.13	5.71
May 19-22, 1917	19	2.95	3.62	0.00	2.22
July 6, 1917	6	2.02	2.02	0.00	2.95
July 15, 1918	15	2.02	2.02	0.00	2.96
August 3, 1919	3	2.22	2.22	1.66	4.10
May 23-27, 1921	26	2.12	3.77	1.36	2.89
June 8-9, 1921	9	2.07	2.33	0.09	5.55
September 21-22, 1924	21	2.95	3.00	0.00	1.08

* No record.

At Waseca, during one month in each year the precipitation was 2 to 2½ times the normal amount. During each of these months there was at least one big storm in which the rainfall was about equal to the normal for the whole month. The largest of these storms was that of August 1 to 3, 1928, when 4.39 inches of rain fell, of which 3.80 inches fell on the first. The precipitation during the other large storms was 3.61, 3.76, and 2.90 inches, respectively, for the years of 1925, 1926, and 1927. Each of these storms covered a 3-day period, but in each case more than 2 inches fell during one 24-hour period.

At Paynesville the largest rain occurred on September 17 and 18, 1926, when 3.97 inches fell. On the 17th, 3.25 inches fell. This storm followed a month of heavy rainfall. The previous 24-hour record precipitation was also 3.25 inches, occurring on June 27, 1920.

The consideration of the time and extent of large rains is of great importance because it is these rains, other factors being normal, that are the real tests of efficiency of a tile drainage system. The amount of precipitation in excess of the soil's capillary capacity must be carried off either over the surface or through tile drains to avoid injury to the plants growing on the soil. This method of disposal of rainfall is what is commonly designated as run-off.

Measurement of Run-Off

At two stations, Meadowlands and Paynesville, the run-off, all of which was discharged through the tile system, was measured by weirs. At Meadowlands a small rectangular weir 0.1 foot wide and 2.5 feet high was installed after being calibrated in the hydraulic laboratory at the University of Minnesota. The weir notch was cut in a sheet of ⅛-inch boiler plate steel which was bolted to the inside of a stilling box 3 feet square and 4 feet deep, the notch in the box being enough larger than that in the plate so that its sides did not touch the discharging stream of water. (See Fig. 9.) The velocity of approach was checked by having the weir notch one foot above the bottom of the box, and also by baffles within and at the rear of the box.

Fig. 9. Measuring Weir and House for Water Level Gage, Meadowlands

At Paynesville a standard Cippoletti weir with a 3-foot crest was used. (See Fig. 10.) At both stations a Bristol continuous-recording pressure gage recorded the head of water over the weir.

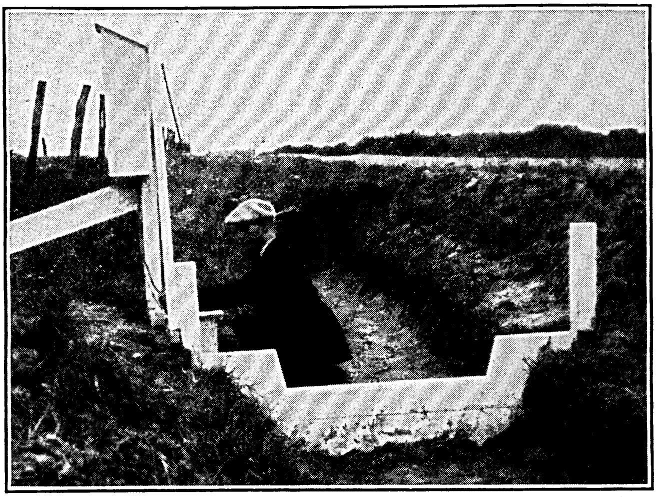

Fig. 10. Cippoleti Weir and House for Water Level Gage, Paynesville

Run-Off

Since the amount of run-off is dependent upon so many variable factors, the percentage of run-off varies widely. Some of the most important factors are: (a) amount and intensity of rain, (b) previous precipitation, (c) transpiration, (d) evaporation, and (e) deep seepage. The first three are by far the most important, altho deep seepage is a noticeable factor at Meadowlands, where there is an abrupt drop of 20 feet to the river at the east edge of the field.

Table 9
Run-Off from Drainage Areas at Meadowlands and Paynesville
Expressed in inches of depth
April 1-October 15, inclusive

Item	Meadowlands					Paynesville				
	1925	1926	1927	1928	Total	1925*	1926	1927	1928	Total
Total run-off, inches	0.52	0.55	0.00	3.59	4.66	0.00	3.16	1.07	0.11	4.34
Total precipitation, inches	20.00	16.72	14.71	26.00	77.43	3.81	25.52	18.62	19.08	67.03
Per cent as run-off	2.60	3.30	0.00	13.80	6.00	0.00	12.40	5.70	0.60	6.60
Rains causing run-off, inches	3.85	2.54	0.00	20.50	26.89	0.00	18.15	9.73	3.44	31.32
Per cent as run-off	13.50	21.60	0.00	17.50	17.30	0.00	17.40	11.00	3.20	13.90
Precipitation above or below normal,† inches	+1.05	−2.23	−4.24	+7.05	+1.63	−3.92	+3.58	−3.32	−2.86	−6.52

* August 1—October 15, inclusive.
† Normal for Paynesville taken from records for St. Cloud.

The total precipitation and total run-off for the Meadowlands and the Paynesville stations are given in Table 9. When the precipitation is below normal, the run-off also is low or becomes zero. This was the case at Meadowlands for the first 8 months of both 1925 and 1926 and for all of 1927. At Paynesville, 1925, the last half of 1927, and 1928 were so dry that no appreciable run-off occurred.

The amount and percentage of run-off for the respective rains at the Meadowlands station are given in Table 10, and those for the Paynesville station in Table 11. All rains of one inch or more and those of less than one inch which cause run-off are listed in these tables.

Meadowlands.—During 1925 and 1926 there was no run-off before September 1, and during 1927 no run-off throughout the year. There was only one rain in 1927 that amounted to more than one inch. During 1928 there was at least one rain each month, from April to October, inclusive, which caused run-off. The summary of rainfall with reference to run-off (see Table 12) shows the widely variable relation between rainfall and resulting run-off and indicates the marked effect of the growth of crops in slowing up or eliminating run-off.

For this station the maximum run-off usually occurs during the first 6 hours after the intense part of the rain and may exceed a rate of one acre-inch per day. The highest **rate** was 1.60 acre-inches on September 6, 1925, when 2.80 inches of rain fell in 9 hours. The maximum rate of discharge exceeded one inch per day three times and 0.50 inch seven times, while the total discharge exceeded 0.50 inch only once. (October 12 to 15, 1928, when 0.77 inch ran off, following 1.47 inches of rain.) The highest total discharge during the **growing season** (May to August, inclusive) was 0.31 inch on July 26, 1928. The maximum rate of discharge is not affected as much by the soil moisture condition as is the total discharge.

Of all rains which caused a run-off, the weighted average run-off for rains less than one inch was 26 per cent for the entire season, that for the growing season being only 21 per cent, and that for early and late rains being 27 per cent; while for rains of one inch or more the weighted average run-off for the entire season was 12 per cent, that for the growing season 5 per cent, and that for early and late rains 20 per cent.

Paynesville.—At Paynesville there was no run-off from July 31, 1925—at which time the measuring gage was installed—to June 20, 1926. The precipitation for that period was low, the accumulated deficiency to June 1, 1926, amounting to 10.36 inches. There were 4 rains in June, all but one being over one inch. Only the last two caused run-off. (See Table 11.) From June 1, 1926, to June 1, 1927, there

Table 10
Precipitation, Ground Water Stages and Movement, and Run-Off—Meadowlands

Item No.	Date of storm	Length of storm, hours	Precipitation during			Max. height of ground water above tile grade at mid-point for spacings of:			Rate of drop of ground water at mid-point, feet per day for spacings of:			Max. rate discharge per day, acre-inch	Length of time tile discharged after storm, hours	Approximate total discharge		Per cent run-off
			Present storm, inches	Previous 7 days, inches	Previous 30 days, inches	60 ft.	90 ft.	135 ft.	60 ft.	90 ft.	135 ft.			Cubic feet	Acre-inches per acre	
	1925															
1	June 2-9	192	2.00	0.18	1.13	0.5	−1.0	1.6	....	....	....	0	....	....	....	...
2	July 8-9	48	1.77	0.71	2.72	0.4	1.0	1.2	....	....	....	0	....	....	....	...
3	Aug. 29-30	48	1.50	0.59	2.16	−1.3	−1.4	−1.4	....	....	....	0	....	....	....	...
4	Sept. 2-3	48	1.05	1.68	3.46	−1.0	−0.3	1.3	....	....	....	1.36	20	1376	0.05	4.8
5	Sept. 6	9	2.80	1.50	4.04	3.1	3.2	3.5	0.65	0.60	0.55	1.60	108	11916	0.47	16.8
6	Sept. 29-30	48	1.39	0	5.16	0.6	0.8	1.2	....	....	....	0	....	....	....	...
7	Oct. 6-8	52	0.57	1.74	2.60	2.7	2.8	2.9	1.05	0.62	0.53	No record	No record	....	....	...
	1926															
8	June 20-23	96	1.23	0.86	3.77	0.5	0.2	1.6	....	....	....	0	....	....	....	...
9	July 8-9	24	1.24	0.17	2.26	0	0	0.5	....	....	....	0	....	....	....	...
10	Aug. 4	24	2.00	0	1.78	−0.5	0	1.4	....	....	....	0	....	....	....	...
11	Aug. 19-20	48	1.17	0.28	2.76	−0.1	1.1	1.7	....	....	....	0	....	....	....	...
12	Sept. 10-11	24	0.56	1.66	3.38	0.5	1.5	1.9	....	....	....	0.04	Next rain	Record incomplete		
13	Sept. 13-14	12	0.55	1.26	3.76	1.7	2.3	2.7	....	....	....	0.04	Next rain	1760	0.07	12.7
14	Sept. 17	8	0.55	1.11	4.21	2.0	2.6	3.2	0.40	0.30	0.20	0.04	102	3430	0.13	23.6
15	Sept. 23	8	0.79	0.66	3.46	2.2	3.0	3.5	0.40	0.65	0.53	0.15	96	3456	0.14	17.7
16	Oct. 1-4	96	1.43	0	4.24	2.6	2.8	3.1	0.40	0.40	0.20	0.19	132	5400	0.21	14.7
	1927															
17	July 13	24	1.13	0	1.74	...	...	...	....	....	....	0	....	....	....	...
18	July 15-16	48	0.99	1.13	2.87	−1.2	−1.3	−0.5	....	....	....	0	....	....	....	...
	1928															
19	April 29-30	30	0.52	0.02	1.26	2.9	2.8	2.8	....	....	....	0.23	Next rain	3320	0.13	25.0
20	May 2	18	0.28	0.52	1.78	2.9	2.9	3.1	0.61	0.40	0.40	0.34	48	4770	0.19	67.8
21	June 15-23	216	4.05	1.22	1.49	2.7	3.1	3.2	0.60	0.73	0.46	0.14	34	3110	0.12	2.9
22	July 6-8	53	2.13	0	6.27	0.8	2.6	3.1	....	0.60	0.61	0.03	24	650	0.03	1.4
23	July 19	6	1.41	1.00	4.49	2.4	2.7	3.0	0.32	0.43	0.35	0.52	54	4875	0.19	13.5
24	July 26	8	0.87	1.41	4.64	2.7	3.2	3.5	0.80	0.80	0.75	0.58	60	7880	0.31	35.6
25	Aug. 15-16	32	2.52	0	4.19	2.8	3.0	3.1	0.60	0.60	0.42	0.03	48	2490	0.10	4.0
26	Aug. 20	8	0.57	2.52	4.45	1.9	2.4	2.7	0.37	0.45	0.35	0.04	36	625	0.02	3.5
27	Aug. 27	8	0.22	0.57	4.15	1.2	1.7	2.2	....	....	....	0.04	20	615	0.02	9.1
28	Aug. 29	8	1.25	0.22	3.80	2.2	2.7	3.0	0.40	0.50	0.40	0.22	88	3095	0.12	9.6
29	Sept. 10	20	1.50	0	4.83	3.1	3.2	3.2	....	....	....	0.84	Next rain	11800	0.46	30.6
30	Sept. 14	3	0.54	1.50	4.25	3.0	3.2	3.6	0.50	0.40	0.40	0.26	Next rain	5600	0.22	40.7
31	Sept. 16	3	0.49	2.04	4.35	3.0	3.2	3.6	0.80	0.70	0.65	0.34	76	4560	0.18	36.7
32	Sept. 20	8	0.15	1.03	4.27	1.3	1.5	2.0	....	....	....	0.11	Next rain	2035	0.08	53.3
33	Sept. 22	4	0.78	0.64	4.42	2.8	3.2	3.6	0.43	0.42	0.50	0.12	56	3170	0.12	15.4
34	Oct. 4-5	20	1.55	0	3.50	3.0	3.1	3.2	....	....	....	0.60	130	12610	0.50	32.2
35	Oct. 8	8	0.20	1.55	5.05	2.4	2.7	3.1	0.40	0.20	0.20	0.02	60	810	0.03	15.0
36	Oct. 12-15	56	1.47	0.35	3.75	3.3	3.3	3.6	0.56	0.46	0.40	1.07	96	19440	0.77	52.4

Table 11

Precipitation, Ground Water Stages and Movement, and Run-Off—Paynesville

Item No.	Date of storm	Length of storm, hours	Precipitation during: Present storm, inches	Precipitation during: Previous 7 days, inches	Precipitation during: Previous 30 days, inches	Max. height of ground water above tile grade at mid-point for spacings of: 100 ft.	Max. height of ground water above tile grade at mid-point for spacings of: 250 ft.	Rate of drop of ground water at mid-point, feet per day for spacings of: 100 ft.	Rate of drop of ground water at mid-point, feet per day for spacings of: 250 ft.	Max. rate discharge per day, acre-inch	Length of time tile discharged after storm, hours	Approximate total discharge: Cubic feet	Approximate total discharge: Acre-inches per acre	Per cent run-off
	1925													
1	July 6	8	1.62	0.03	2.38	0	0	...	...	...	No record	......	...	...
2	July 8	20	3.13	1.62	4.00	0	3.2	...	0.60	...	No record	......	...	...
3	Aug. 7-8	24	1.07	0.13	0.33	0	0	...	...	...	0	......	...	...
4	Sept. 4-5	15	1.12	0.64	1.80	0	0	...	...	...	0	......	...	...
	1926													
5	June 11-13	44	1.38	0	0.51	0	0	...	...	...	0	......	...	...
6	June 15-16	32	1.24	1.38	1.70	0	0	...	...	...	0	......	...	...
7	June 20	6	1.95	1.24	2.93	0	0	...	...	0.29	Next rain	226,000	0.30	13.2
8	June 23	1	0.31	3.05	4.86	0	0	...	...	...	120			
9	July 9	16	2.99	0	4.90	0.1	0.5	...	...	0.33	199	231,000	0.31	10.3
10	Aug. 18-20	36	3.20	0.80	3.02	0	0.2	...	...	0.11	222	240,000	0.32	10.0
11	Sept. 1	1	0.60	0	5.32	0	0.2	...	...	0.02	20	648	0.001	0.2
12	Sept. 2-4	48	1.63	0.60	5.22	0	0.4	...	...	0.04	Next rain	121,000	0.16	9.8
13	Sept. 7-8	20	1.61	2.23	6.32	0	3.0	...	0.38	0.23	Next rain	327,000	0.43	18.1
14	Sept. 11	8	0.77	1.73	7.50	0	3.0	...	0.29	...	Next rain			
15	Sept. 17-18	32	3.97	0.86	7.94	3.3	4.1	0.80	0.60	0.55	Next rain	1,062,000	1.41	31.1
16	Sept. 23	12	0.56	3.98	8.68	2.0	3.0	0.45	0.25	...	198			
17	Oct. 3	12	0.56	0.08	9.33	1.8	3.2	0.17	0.36	0.06	120	166,000	0.22	39.3
	1927													
18	April 4	20	1.01	0.31	1.76	...	...	...	...	...	No record	......	...	...
19	April 19	12	1.15	0.43	2.82	2.2	3.2	0.12	0.32		Next rain	Broken record		...
20	April 28	2	0.41	0.07	3.13	1.0	2.5	...	...	0.03	Next rain	51,400	0.07	17.1
21	May 2	8	0.94	0.46	3.54	1.6	4.0	0.25	0.40	0.21	Next rain	382,900	0.51	40.5
22	May 9-10	48	0.32	1.02	3.20	1.2	3.4	0.10	0.25	...	Next rain			
23	May 20-23	72	1.81	0.11	1.96	3.0	4.3	0.48	1.08	0.13	Next rain	269,500	0.37	20.5
24	June 2-4	32	0.40	0	2.30	1.4	1.4	...	...	...	Next rain	Broken record		...
25	June 9-11	48	1.43	0.40	2.68	2.0	2.8	0.15	0.46	0.04	Next rain	56,100	0.07	4.9
26	June 20-22	48	0.74	0	1.99	1.4	0.5	...	...	...	Next rain	17,700	0.02	2.7
27	July 1	8	0.57	0.02	2.57	1.0	0	...	...	...	Next rain	2,160	0.003	0.3
28	July 3	5	0.32	0.59	2.23	0.9	0	...	...	...	144			
29	July 12	7	0.47	0	1.65	0.6	0	...	...	...	24	0	...	...
30	July 15-16	24	2.33	0.47	2.12	0.6	0.6	...	...	0.03	129	20,100	0.03	1.3
	1928													
31	May 2-3	24	0.54	0.11	1.53	...	...	...	...	...	366	80,220	0.11	20.4
32	June 16	4	1.15	0.84	1.61	0.1	0	...	...	...	0	......	...	...
33	July 12	2	1.41	0.66	3.84	0	0	...	...	...	0	......	...	...
34	July 17	4	1.57	1.46	3.71	0	0	...	...	...	3	806	0.001	0.1
35	Aug. 1	8	1.33	0.28	5.20	0.8	0.7	...	...	...	6	2,700	0.004	0.3
36	Aug. 14-20	144	1.43	0	3.66	0	0	...	...	...	0	......	...	...
37	Sept. 12-16	96	2.50	0.04	3.21	0	0	...	...	...	0	......	...	...

Table 12
Summary of Rainfall with Reference to Run-Off
1925 to 1928

Size of rain, inches	Meadowlands						Paynesville					
	Preceded by		Rains causing run-off				Preceded by		Rains causing run-off			
	Less than 1 inch in last 7 days, no.	1 inch or more in last 7 days, no.	Total no.	Time of year, month	No. per month	Average per cent run-off	Less than 1 inch in last 7 days, no.	1 inch or more in last 7 days, no.	Total no.	Time of year, month	No. per month	Average per cent run-off
When less than 3 inches fell in last 30 days												
0.10-0.99	69		2	April	1	25.0	46		6	May	1	20.4
				May	1	67.8				June	2	2.7
										July	3	0.3
0.10-0.99		5	0					4	0			
1.00-1.99	5		0				8		3	April	1	*
										May	1	20.5
										June	1	4.9
1.00-1.99		0	0					2	1	June	1	13.2
2.00-3.99	2		0				1		1	July	1	1.3
2.00-3.99		1	1	June	1	3.0		0	0			
When 3 inches or more fell in the last 30 days												
0.10-0.99	17		3	Aug.	1	9.1	17		4	April	1	17.1
				Sept.	2	16.5				May	1	40.5
										Sept.	1	0.2
										Oct.	1	39.3
0.10-0.99		17	9	July	1	35.6		6	4	May	1	40.5
				Aug.	1	3.5				June	1	13.2
				Sept.	7	28.6				Sept.	2	26.6
1.00-1.99	7		5	Aug.	1	9.6	4		2	Aug.	1	0.3
				Sept.	1	30.6				Sept.	1	9.8
				Oct.	3	33.3						
1.00-1.99		2	2	July	1	13.5		2	2	July	1	0.1
				Sept.	1	4.8				Sept.	1	18.1
2.00-3.99	2		2	July	1	1.4	4†		2	Aug.	1	10.0
				Aug.	1	4.0				Sept.	1	31.1
2.00-3.99		1	1	Sept.	1	16.8		0	0			

* Incomplete record.
† No record of run-off for rain of July 8, 1925.

was an excess in precipitation of 8.22 inches. With the exception of the time during which the ground was frozen during the winter, there was nearly a continuous discharge from the tile from June 20, 1926, to July 12, 1927. The rate of discharge ranged from less than 0.01 cfs to a maximum of about 5 cfs. During this period nearly all rains caused run-off, but after July 12, 1927, to the end of 1928 only one rain of less than one inch (May 2 to 3, 1928) caused run-off, and only 3 of the 7 rains of over one inch caused any run-off.

A summary of the rainfall with reference to the run-off is given in Table 12.

At Paynesville the maximum rate of run-off occurs one to 4 hours after the beginning of a storm, and as nearly as could be determined from the records it was within 2 hours after the intense part of the storm. On July 8, 1926, when 2.84 inches of rain fell in an hour, the maximum rate of run-off (0.33 acre-inches per day) occurred within 2 hours after the beginning of the storm. The total run-off for this storm was 0.31 acre-inches per acre.

Because of the difference in soil, topography, area, and the design, the Paynesville tile system reached the maximum discharge rate sooner but continued to discharge water longer after a storm than did the Meadowlands tile system.

At Meadowlands the area in the drainage basin is small (7.5 acres), level, and of fairly uniform soil, while at Paynesville the area is larger (208 acres), rolling, including many small pockets and swales, and of variable soil formation. (See page 9.) Several surface inlets were installed in the depressions at the Paynesville station, thus giving a greater and quicker concentration of the run-off through the tile lines than would otherwise occur.

As a general rule for the stations at Meadowlands and Paynesville the percentage of run-off is less for the larger than for the smaller rains which cause run-off, and is less during the growing season than for early and late rains. Also, the greater the intensity, the greater the run-off, other factors being equal.

In general when there has been less than 3 inches of rain during the previous 30 days, a rain will cause little if any run-off. Rains of less than one inch occurring during the growing season are not likely to cause run-off unless they are preceded by 4 inches or more of rain in the previous 30 days. Practically all rains of more than one inch when preceded by 3 inches or more in the previous 30 days will cause run-off and also a decided rise in the ground water table.

WHAT CONSTITUTES GOOD DRAINAGE

The foregoing discussion has shown the great variation between rainfall and run-off and the great influence of the season of the year, especially the growing season, on the amount and rate of accumulation of excess water and the consequent amount and rate of run-off. The next logical step, then, is the consideration of what really constitutes good drainage.

The primary purpose of drainage (12) is to remove the excess or injurious water, but the ultimate and more far-reaching purpose is insurance against subsequent drouth. When the water table is high during the early growing season, the root penetration will be very shallow. Later in the season when the water table is dropping rapidly, the roots, by that time more or less stunted and practically mature, cannot keep up with the lowering water table and the plant soon suffers, or dies for lack of moisture. If the water table could have been held lower when the roots were making their greatest growth, their penetration would have been greater and the subsequent damage by drouth greatly reduced.

Kopecky (8) states that for optimum conditions for the root growth of grain crops 20 to 30 per cent of the total pore space should be filled with air and the remainder with water. From 15 to 50 per cent of the total pore space of loam soils is of non-capillary size (see Fig. 7). That is, that amount of pore space would be occupied by air if the excess water could be drained out. Since surface soils contain more non-capillary pore space than subsoils of the same moisture equivalent, the air space in the first foot of a well drained soil would be greater than that given from the curves.

The most important point in the effectiveness of a tile drainage system is the distance between the surface and the ground water table at the mid-point between the tile lines. Rothe (15) suggests 50 cm. for cultivated crops and 40 cm. for hay crops. Altho this will depend upon the types of crops, their root systems, and water requirements, an average value can, as a rule, be used for various types of crops grown in the rotation.

The writer has observed that crops will not be injured if the water table at the mid-point is kept one foot or more below the surface at all times, and two feet or more below the surface 75 per cent of the time. (Table 13.) Even tho the water comes within one foot of the surface but not over the surface, the injury will not be great for most crops if it can be lowered again in a few hours. The grass crops are much more tolerant of water than the ordinary row crops. As a rule the truck crops are the most sensitive to excess water and therefore should have the most effective drainage system.

Table 13
Time Ground Water, at Mid-Point Between Tile Lines, Was Within the Root Zone

Location	Subsoil: Type	Subsoil: Moisture equivalent	Tile spacing, feet	Tile depth, feet	Maximum continuous period, hours: 1925 May 1-Aug. 31	1925 Sept. 1-Oct. 15	1926 May 1-Aug. 31	1926 Sept. 1-Oct. 15	1927 May 1-Aug. 31	1927 Sept. 1-Oct. 15	1928 May 1-Aug. 31	1928 Sept. 1-Oct. 15	Percent of total time: 1925 May 1-Aug. 31	1925 Sept. 1-Oct. 15	1926 May 1-Aug. 31	1926 Sept. 1-Oct. 15	1927 May 1-Aug. 31	1927 Sept. 1-Oct. 15	1928 May 1-Aug. 31	1928 Sept. 1-Oct. 15	Average May 1-Aug. 31	Average Sept. 1-Oct. 15
					Ground water within one foot of surface																	
Aitkin		12	200	5.0					0	0	0	0					0	0	0	0	0	0
	Sandy	10	295	4.5					0	0	144	250					0	0	11	33	8	13
	loam	12	600	4.0	0	0	0	720	624				0	0	0	67	30				9	33
		10	800	5.0	0	0	0	720	1080				0	0	0	67	63				18	33
Meadowlands	Silt	27	60	3.4	0	48	0	12	0	0	84	96	0	6	0	1	0	0	5	27	1	8
	loam	27	90	3.4	0	48	0	144	0	0	96	240	0	8	0	20	0	0	13	44	3	18
		27	135	3.4	0	120	0	168	0	0	120	264	0	17	0	36	0	0	20	49	5	25
Paynesville	Loam	21	100	4.0	0	0	0	12	0	0	0	0	0	0	0	1	0	0	0	0	0	0
		21	250	4.2	18	0	0	78	120	0	0	0	1	0	0	10	8	0	0	0	2	3
Waseca	Clay	35	45	3.4	24	0	0	216	24	0	0	0	1	0	0	20	1	0	0	0	1	5
		30	125	3.6	18	0	0	48	24	0	0	0	1	0	0	4	1	0	0	0	1	1
					Ground water within two feet of surface																	
Aitkin		12	200	5.0					0	72	48	288					0	7	2	40	1	20
	Sandy	10	295	4.5					48	480	552	552					10	62	66	90	60	73
	loam	12	600	4.0	0	0	0	864	1200				0	0	0	80	80				23	40
		10	800	5.0	456	384	360	960	1728				63	51	20	89	92				44	70
Meadowlands	Silt	27	60	3.4	0	144	0	192	24	0	168	264	0	24	0	36	1	0	23	56	6	29
	loam	27	90	3.4	0	216	0	360	54	0	240	264	0	38	0	62	3	0	35	70	10	42
		27	135	3.4	0	240	24	888	120	0	264	480	0	42	2	82	10	0	42	77	13	51
Paynesville	Loam	21	100	4.0	0	0	0	72	84	0	0	0	0	0	0	7	4	0	0	0	1	2
		21	250	4.2	90	0	0	792	360	0	48	0	3	0	0	73	22	0	1	0	5	18
Waseca	Clay	35	45	3.4	60	0	0	240	80	0	0	0	2	0	0	22	4	0	0	0	1	6
		30	125	3.6	78	0	0	216	120	0	0	0	3	0	0	20	4	0	0	0	2	5

GROUND WATER MEASUREMENTS

To secure evidence of the effectiveness of drainage that might be expressed in physical units, it was necessary to measure the fluctuations of the ground water table. To accomplish this, a line of test wells was set at right angles to the direction of the tile line. These wells were located at the tile lines, 5 and 10 feet away, and at various intermediate distances according to the spacing of the tile lines. (See Figs. 2, 3, 4, and 6.) The wells were constructed by boring holes 6 feet deep with a post auger and lining them with 4- or 5-inch drain tile on end. The elevation of the top of each well was obtained with an engineer's level, and the distance down to the ground water was measured to the nearest 0.01 foot from the top of the well. It was the original plan to have the readings taken immediately after each rain, then 6, 12, and 24 hours thereafter for the first day, then each succeeding day as long as an appreciable drop occurred, and then once each week until the wells were dry, but in most cases it was impossible to get the local observers to follow any schedule. They took the readings whenever it was convenient. The value of the data was greatly reduced by not having been taken as scheduled.

GROUND WATER FLUCTUATIONS

The ground water fluctuations are caused by precipitation, transpiration, evaporation, run-off, and deep seepage. In order that gravity water may be present in the soil, the soil moisture content must be above the capillary capacity. Until enough precipitation has fallen to bring the soil moisture content above this capacity, the ground water table will remain stationary or continue to drop even below the tile lines. However, after the "hydraulic slope"—defined by Schlick (17, p. 35) as the "head" causing flow toward the tile drains—has become less than one to 5 feet in 100 feet, depending upon the soil and the spacing of the tile, the lowering of the ground water table is due to deep seepage alone.

In many cases the permanent ground water table is many feet below the surface. The temporary saturated condition of the surface soil is due to a partially impervious subsoil or to one in which the frictional resistance is so great that it takes many weeks for the water to get through. The rate of downward percolation varies greatly, depending upon the texture of the substrata. The drop of the ground water table due to deep percolation and to transpiration is sometimes greater than the movement to the tile lines. It is hard to separate the different water movements as they all work contemporaneously. Better soil drainage, which means greater or more rapid lowering of the water table, gives an opportunity for more vigorous plant growth, which in turn transpires more water and opens up the subsoil by root penetration.

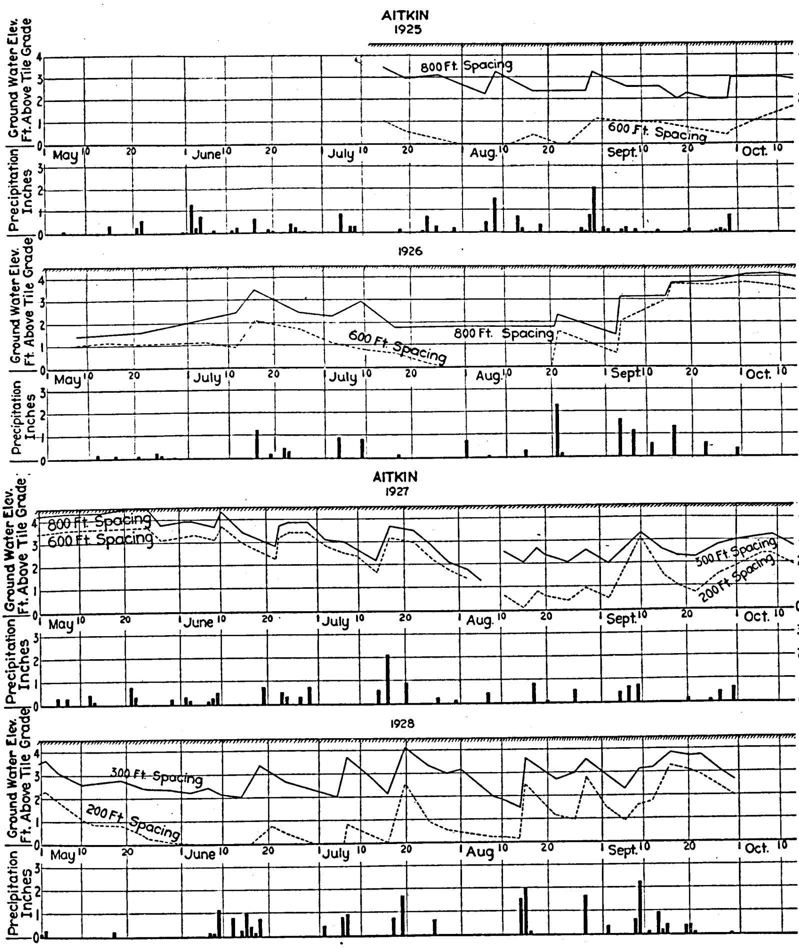

Fig. 11. Ground Water Profiles at Mid-Point Between Tile Lines, and Daily Precipitation, Aitkin, Minnesota

Altho the roots of most of the ordinary cultivated crops will not penetrate a saturated soil to any extent, they may live for a few days in a saturated soil if the water is moving and does not cover the surface. In case the water comes to the surface and the weather is hot, the plants will scald within a few hours. Since the soil immediately above a saturated soil approaches saturation, it is better to design the drainage system so that the maximum height of the ground water table is at least one foot below the surface, except for extreme conditions when it may rise within the first-foot zone for only a few hours duration.

The peak height of the ground water table and the daily precipitation are plotted in Figs. 11 to 14. The average peak height of ground

Table 14
Height of Ground Water Above Tile Grade at Mid-Point Between Tile Lines

Location	Subsoil: Type	Subsoil: Moisture equivalent	Tile spacing, feet	Tile depth, feet	1925: Av. for May 1-Aug. 31, feet	1925: Av. for Sept. 1-Oct. 15, feet	1926: Av. for May 1-Aug. 31, feet	1926: Av. for Sept. 1-Oct. 15, feet	1927: Av. for May 1-Aug. 31, feet	1927: Av. for Sept. 1-Oct. 15, feet	1928: Av. for May 1-Aug. 31, feet	1928: Av. for Sept. 1-Oct. 15, feet	Grand average: Av. for May 1-Aug. 31, feet	Grand average: Av. for Sept. 1-Oct. 15, feet	Maximum height, feet
Aitkin		12	200	5.0					0.6	1.8	0.8	2.2	0.7	2.0	3.3
	Sandy	10	295	4.5					2.4	2.7	2.7	3.2	2.7	3.0	4.2
	loam	12	600	4.0	0.6	0.9	0.9	3.2	3.1				1.6	2.0	4.0
		10	800	5.0	2.8	2.8	2.1	3.6	3.7				2.8	3.2	5.0
Meadowlands	Silt	27	60	3.4	0.0	0.7	0.0	1.2	0.1	0.0	0.8	1.6	0.2	0.7	3.0
	loam	27	90	3.4	0.0	0.8	0.0	1.8	0.2	0.0	1.1	2.0	0.3	0.8	3.2
		27	135	3.4	0.0	1.3	0.1	2.3	0.4	0.0	1.3	2.4	0.4	1.1	3.6
Paynesville	Loam	21	100	4.0	0.0	0.0	0.0	1.0	0.7	0.0	0.0	0.0	0.1	0.3	3.2
		21	250	4.2	0.0	0.0	0.0	2.4	0.9	0.0	0.1	0.0	0.3	0.8	4.2
Waseca	Clay	35	45	3.4	0.1	0.1	0.0	1.1	0.2	0.0	0.0	0.0	0.3	0.1	3.4
		30	125	3.6	0.1	0.2	0.0	1.0	0.3	0.0	0.0	0.0	0.4	0.1	3.2

water table for each year is given in Table 14. Typical ground water profiles immediately after rains and also at given later dates are shown in Figs. 15 to 21.

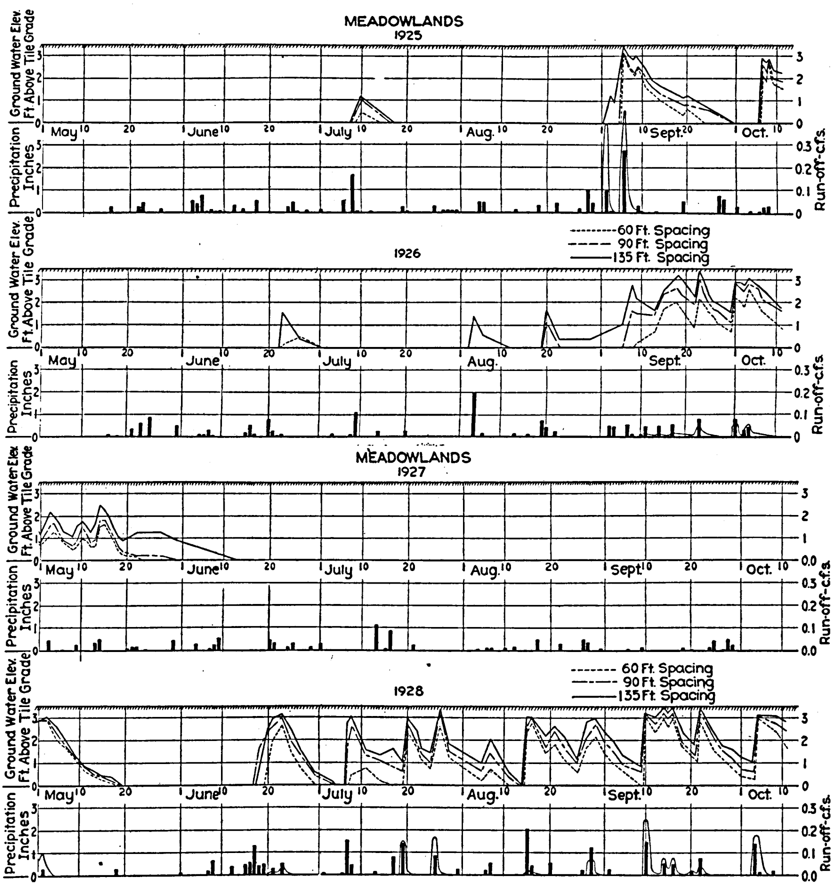

Fig. 12. Ground Water Profiles at Mid-Point Between Tile Lines, and Daily Precipitation, Meadowlands, Minnesota

Aitkin.—The ground water curves for Aitkin between July, 1925, and July, 1927, were for tile spacings of 600 and 800 feet, while for the remainder of 1927 and for 1928 the curves were for spacings of 200 and 300 feet, intermediate lines having been installed during July and August, 1927.

If the precipitation had not been studied, the position of the ground water curves for 1925 and for 1926 up to September 1 would alone have indicated that spacings of 600 and 800 feet were satisfactory for that type of soil, while for the remainder of 1926 and the first half of

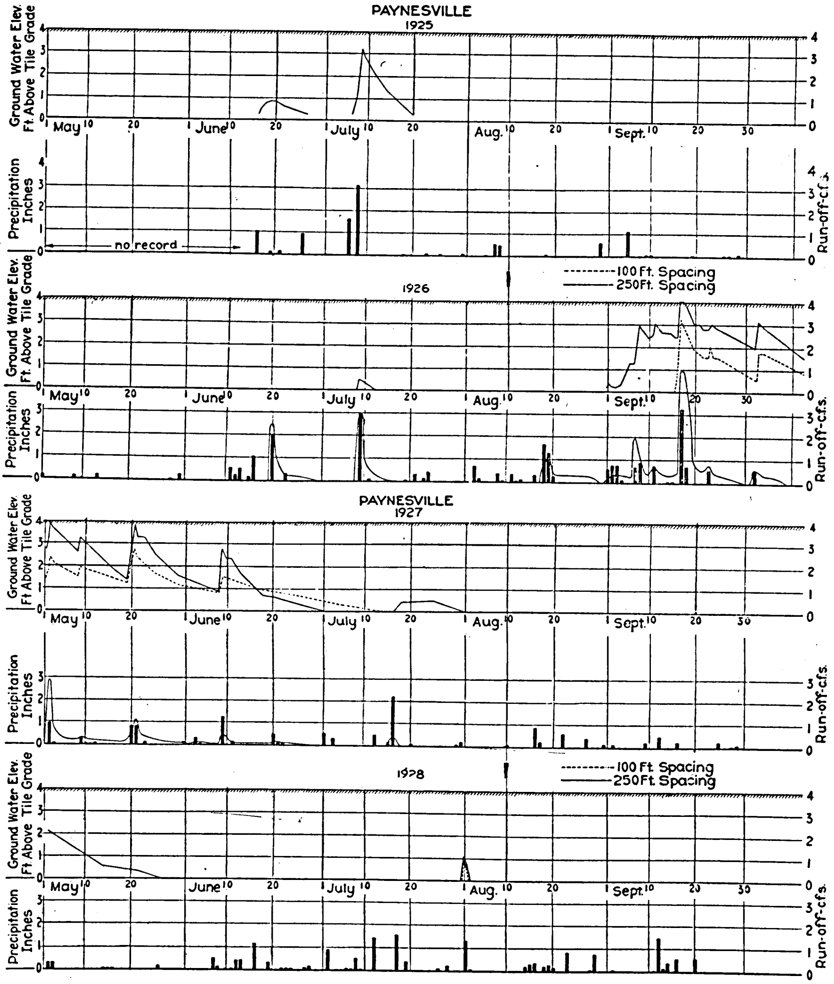

Fig. 13. Ground Water Profiles at Mid-Point Between Tile Lines, and Daily Precipitation, Paynesville, Minnesota

1927 the ground water was within a foot of the surface the greater part of the time (see Table 13). A study of the precipitation records showed that the precipitation for the first 7 months of 1926 was 6.15 inches below normal, while in August, September, and October it was 2½ inches above normal for those months. When the precipitation was low, the ground water was low. In September, after the soil moisture content had increased beyond the capillary capacity and crops had ceased to draw heavily on the moisture supply, the ground water rose rapidly. Altho the precipitation for the early part of 1927 was below normal, the excess from the previous fall was sufficient to keep the ground water

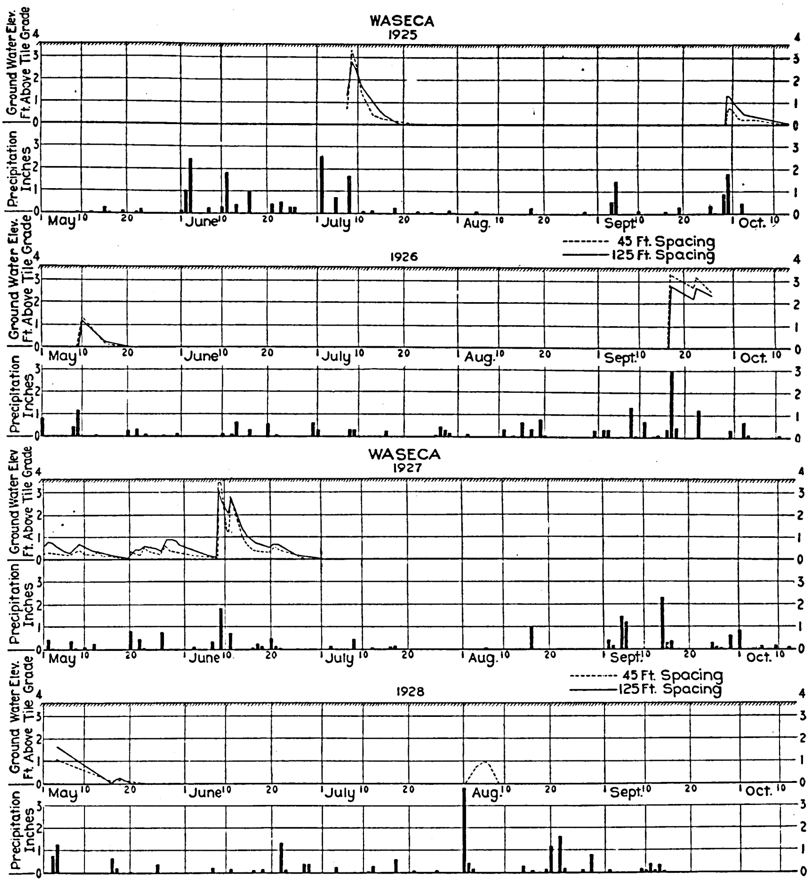

Fig. 14. Ground Water Profiles at Mid-Point Between Tile Lines, and Daily Precipitation, Waseca, Minnesota

table high, the water remaining within a foot of the surface until the middle of July for the 800-foot spacing and within 18 inches of the surface for the 600-foot spacing. During the two seasons in which the ground water observations for the 600- and 800-foot spacings were made, the water was within one foot of the surface 17 per cent and 25 per cent of the time (see Table 13 and Fig. 11). During July and August, 1927, the intermediate tile lines were installed making spacings of 200 and 300 feet, the wider spacing in the coarser-textured soil. While the precipitation for 1928 was above normal, being above every month except May during the growing season, the 200-foot tile spacing held the ground water table down more that one foot below the surface at all times. The ground water was within the second foot only 8 per cent of the total time, and nearly all of this stage was after September 1. For the 300-

foot spacing there was a period of 10 days in the later part of September, 1928, when the water table was within one foot of the surface. The next longest period was 5 days in July of the same year. The ground water was within the first-foot zone 10 per cent and within the second-foot zone 65 per cent of the total time. For the most part the stages occurred after September 1. (See Fig. 11.)

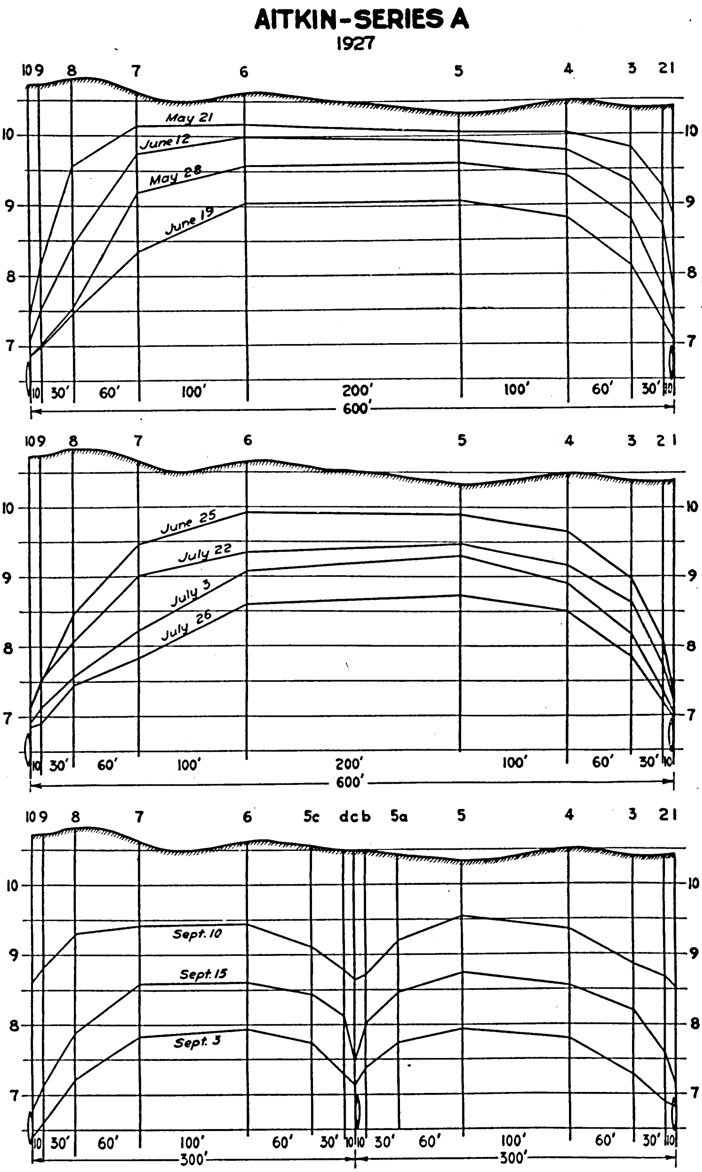

Fig. 15. Ground Water Profiles for Different Tile Spacings, Aitkin—Series A, 1927

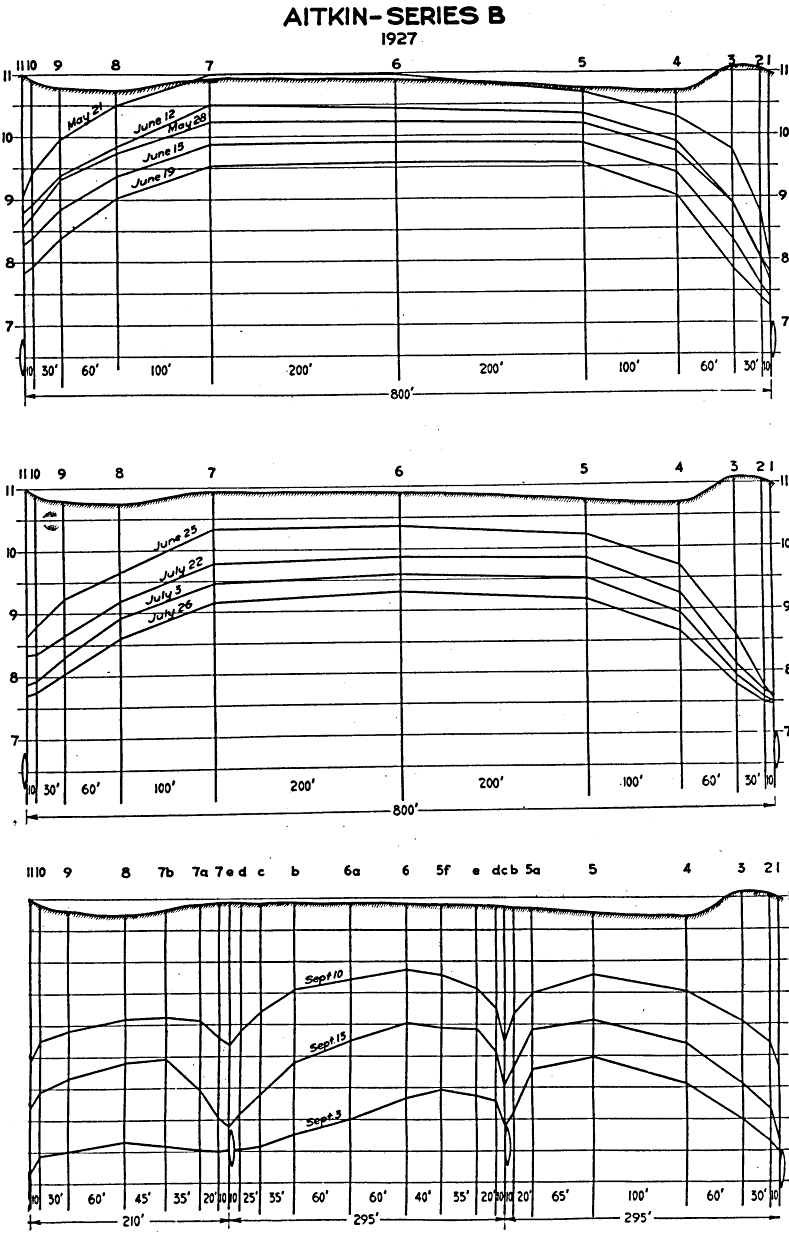

Fig. 16. Ground Water Profiles for Different Tile Spacings, Aitkin—Series B, 1927

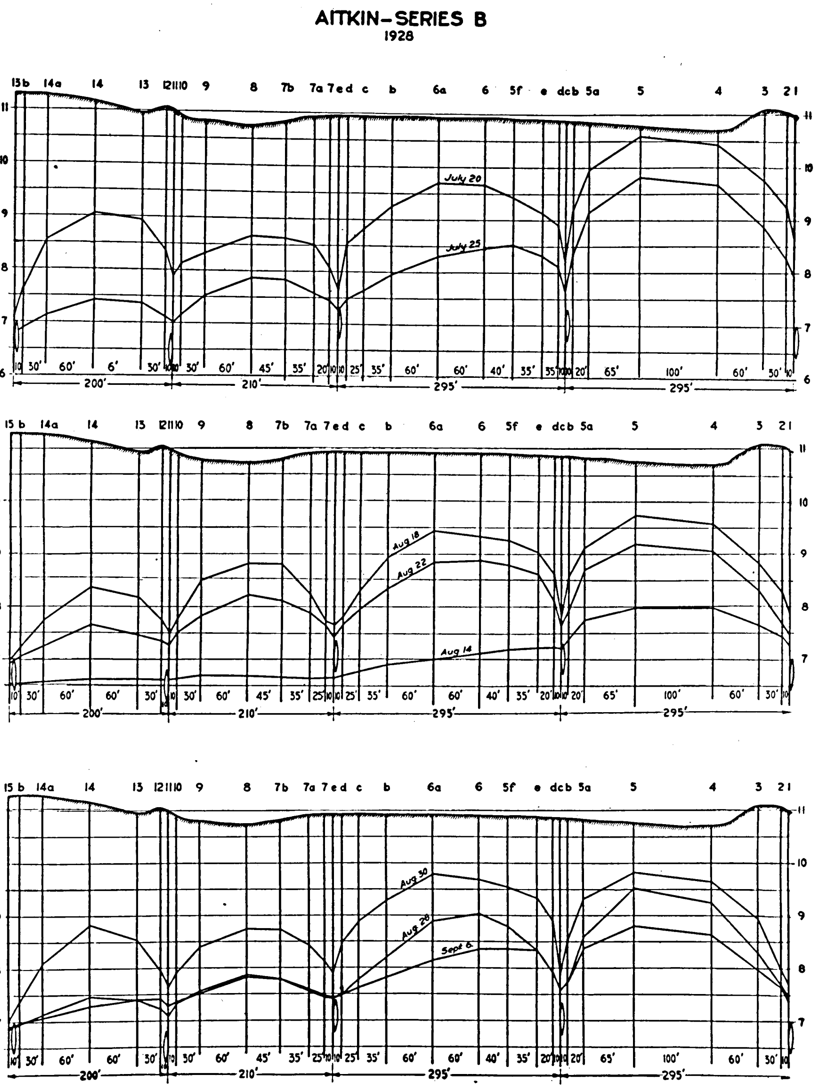

Fig. 17. Ground Water Profiles for Different Tile Spacings, Aitkin—Series B, 1928

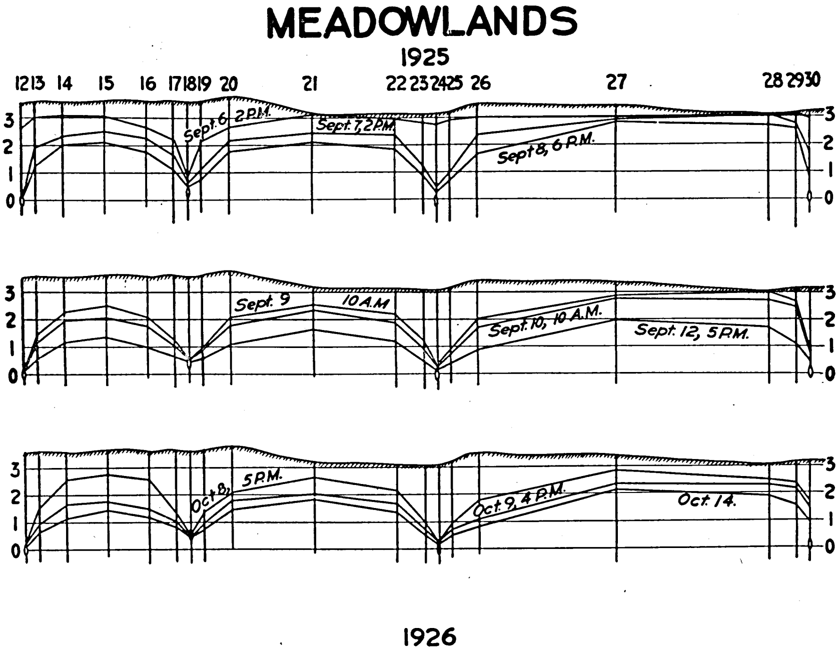

Fig. 18. Ground Water Profiles for Different Tile Spacings, Meadowlands, 1925, 1926

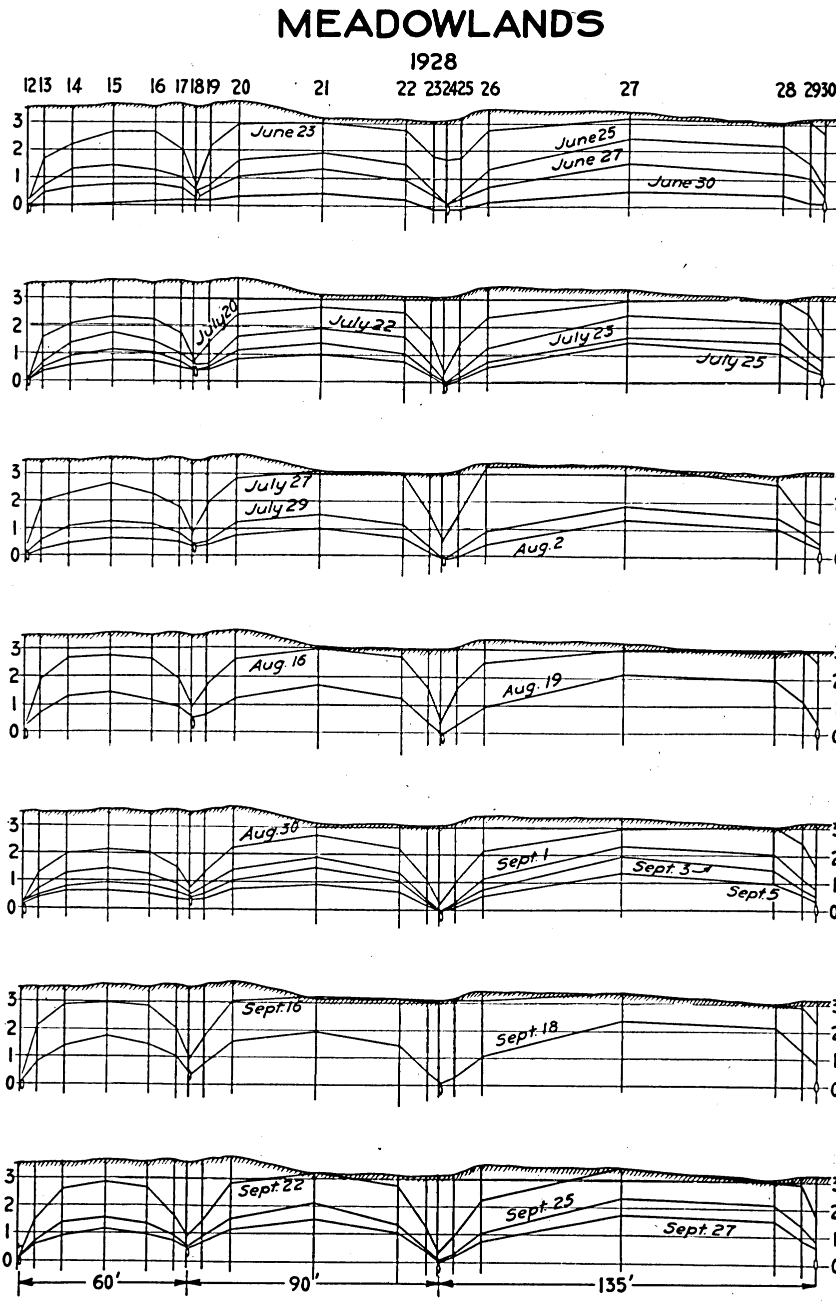

Fig. 19. Ground Water Profiles for Different Tile Spacings, Meadowlands, 1928

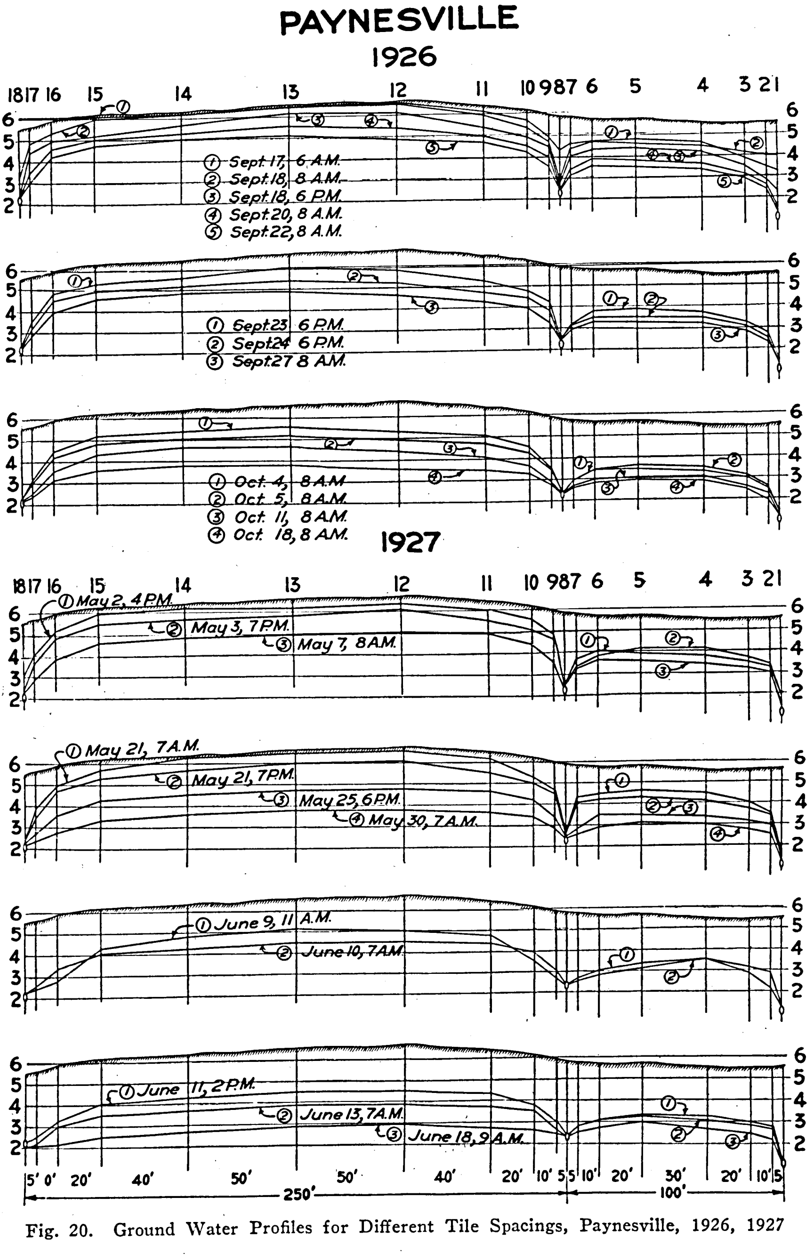

Fig. 20. Ground Water Profiles for Different Tile Spacings, Paynesville, 1926, 1927

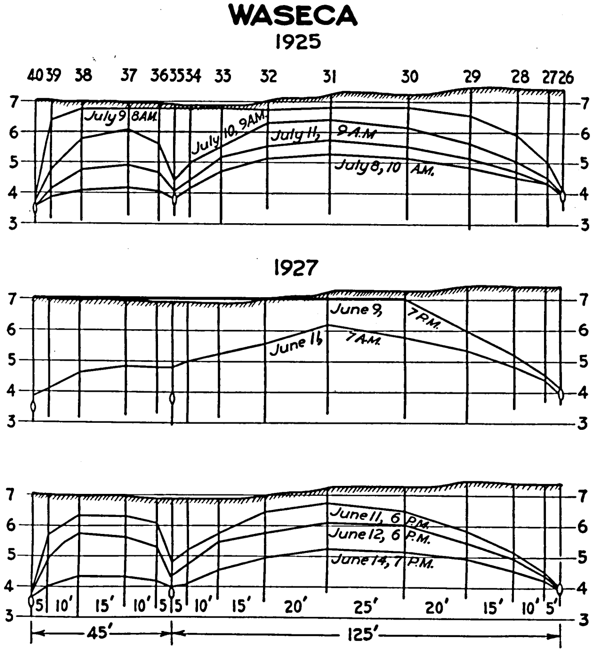

Fig. 21. Ground Water Profiles for Different Tile Spacings, Waseca, 1925, 1927

Meadowlands.—At Meadowlands, between May 1 and August 31 of both 1925 and 1926 the ground water table was usually below the tile grade and at no time was it within 2 feet of the surface. (See Fig. 12.) Both of these years after September 1 the ground water came much nearer the surface, being within one foot of the surface 4 per cent, 14 per cent, and 27 per cent of the time for the respective tile spacings of 60, 90, and 135 feet. The ground water was within the second-foot zone 30 per cent, 50 per cent, and 62 per cent of the time for the same respective tile spacings. (See Table 13.) During 1927, with the exception of May, the ground water table was below the tile grade. In 1928, the only year in which the precipitation was above normal, the relative efficiency of the different tile spacings, was well shown. (See Fig. 12.) The ground water table was high at the beginning of the season, but dropped rapidly through May as during that month there were only two small rains of about ¼ inch each. The soil moisture supply was depleted so much that it took about 3½ inches of rain from June 7 to 17 to bring the soil moisture content above its capillary capacity. From May 1 to August 31 the ground water table was within the first-foot zone 5 per cent, 13 per cent, and 20 per cent of the time for the respective tile spacings of 60, 90, and 135 feet, and within the second-foot zone 23 per cent, 35 per cent, and 42 per cent of the time for the same respective spacings. (See Table 13.) From September 1 to October 15 the ground water table was within the first-foot zone 27 per cent, 44 per cent, and 49 per cent of the time, and within the second-foot zone 56 per cent, 70 per cent, and 77 per cent of the time for the same respective tile spacings.

Paynesville.—At Paynesville, there was only one rain in 1925 that caused the ground water table to rise more than a foot above the tile. This was one of 3.13 inches on July 8, preceded by one of 1.62 inches on July 6. The period from July 10, 1925, to June 10, 1926, was so dry that there was a deficiency of 13.33 inches precipitation.

In 1926 neither a 2-inch rain on June 20 nor a 3-inch rain on July 9 raised the ground water table above the tile. The precipitation for August and September continued above normal, and after September 1 the ground water table showed a decided rise, being within the one-foot zone 1 per cent and 10 per cent of the time and within the second-foot zone 7 per cent and 73 per cent of the time for the respective tile spacings of 100 and 250 feet. During May and June of 1927 the ground water table was within the first-foot zone 0 per cent and 16 per cent of the time, and within the second-foot zone 8 per cent and 45 per cent of the time for the same respective tile spacings. For the remainder of 1927 and all of 1928 the ground water table was low, being below the tile most of the time. (See Table 13 and Fig. 13.)

Waseca.—The wells were not installed at Waseca until July 6, 1925. Consequently there was no record of the ground water table following the large rains in June and the first two in July. After the installation of the wells, there were only 3 storm periods which caused the water table to rise within two feet of the surface. (See Fig. 14.) Owing to lower elevation of the surface and the consequent surface flooding, the narrow tile spacing appeared to be not as effective as the wider spacing. This difficulty could have been remedied by installing a surface inlet in the lowest spot (as shown in Fig. 5).

There were several large rains which did not cause the water table to rise above the tile, one of these being the largest 24-hour storm on record for this station, when 3.80 inches fell on August 1, 1928. Most of this ran off over the surface.

With the precipitation history, the physical characteristics of the soil, the fluctuation of the water table, and the influence thereon of precipitation and plant growth, available as presented in the discussion up to this point, the way is now opened for consideration of suitable drainage procedure and determination of a working formula for tile drainage design.

PROPER SPACING AND DEPTH OF TILE DRAINS

Natural determining factors.—The type of soil, the type of crop, and the climatic conditions are the determining factors in the proper spacing and depth of tile lines. As a general rule the gently rolling lands do not present much of a problem as they have fair natural drainage except in the depressions. In such cases the tile lines are run up the approximate center of these depressions. The flat lands with poor natural drainage are the ones which require a thorough investigation in order to design a system with the proper spacing and depth.

Doubtless, through a series of years, vigorous crops—especially the deep-rooting types—tend to improve subdrainage conditions by a slight opening up of the subsoil, thus making it more responsive to tile drainage. However, the chief influence of crops upon proper design of tile drainage systems is a result of the facts that different types of plants vary widely both in their normal rooting depths and in their tolerance for excess water in the soil, so that subdrainage does not have to be as effective for the shallower-rooting or for the more water-resistant as it does for the deeper-rooting crop types or those more sensitive to excess water in the soil.

The limiting conditions of this study beyond the writer's control have not permitted a close scientific study of plant development in relation to excess free water in the soil, so that this phase of the problem of tile drainage design is considered outside the scope of this discussion. Therefore in the following final analysis of the data covered in this study and in the development of a practical rule of design the writer confines the argument to certain soil characteristics which he believes to be the most potent factors governing the effectiveness of any tile drainage system.

Shape of the ground water curve between two tile lines.—Directly over the tile line the downward movement of the water is so rapid that the soil seldom, if ever, becomes completely saturated, except when there is flooding from higher lands. Whenever the water must pass through a greater lateral than vertical distance to reach the tile line, the slope of the ground water surface becomes very much flatter.

The general shape of the ground water surface between two tile lines in mineral soils is that of a semi-ellipse of the form

$$y^2 = b^2 - \frac{b^2x^2}{a^2} \qquad (1)$$

in which y and x are the rectangular co-ordinates to the water table with two adjacent tile drains at the vertices, a = ½ the major axis or ½ the spacing of the tile lines, b = ½ the minor axis or the depth of the tile. (See Figs. 15 to 21.)

In nearly all cases, the measured y values are greater than the calculated values, especially when the ground water is near the surface. This may be attributed to the following pertinent facts about the surface soil: (a) A surface soil contains more non-capillary pore space than a subsoil with the same moisture equivalent. (b) The rate of moisture depletion by plants is much greater in the surface than in the subsoils, due to transpiration and evaporation. (c) Therefore the rate of drop of the ground water through the first foot is much faster than through the subsoil. Consequently the surface of the ground water table between the tile lines is flatter than a theoretical elliptical curve as given by Equation 1.

The equation of the ground water curve is not of vital importance in most cases of ordinary farm drainage, as all that is usually wanted in such cases is to know how deep and how far apart the tile lines must be placed in a given soil for the greatest benefit to the crops to be grown. However, with the continued advances in plant science, the location of the drains with reference to the rows in cases of widely spaced row crops may become important. Therefore the writer has considered it advisable to present the foregoing equation and the brief discussion thereof.

Rate of drop of the ground water at mid-point between tile lines.—The rate of drop of the ground water at the mid-point varies considerably according to the previous moisture condition of the soil and to the temperature, being very rapid when the subsoil is low in moisture content and warm. (See Tables 10 and 11 and Figs. 11 to 14.) The average rate of drop for each of the first four 6-inch intervals for each of the four observation stations is given in Table 15. When the subsoil is low in moisture content the greatest movement is downward, while when the subsoil is already saturated the movement is lateral. In most cases the lateral movement is much slower than the vertical. In the early spring and late fall, when both the soil and precipitation are cold, the movement is much slower, but at these times there is no need of having the free water removed so quickly. (See Table 15.) A heavy crop on the ground accelerates the drop through transpiration by the plants. Then, too, when the transpiration is great, the reservoir for additional storage of water is rapidly enlarged, as will readily be understood when it is realized that the maximum transpiration for corn is ¼ inch per day (3). For other grains it is slightly less.

Table 15
Average Rate of Drop of Ground Water at Mid-Point Between Tile Lines

Location	Subsoil		Tile spacing, feet	Tile depth, feet	Rate of drop in feet per day from surface downward									
					May 1 to August 31					September 1 to October 15				
	Type	Moisture equivalent			Maximum, feet	First 6 inches, feet	Second 6 inches, feet	Third 6 inches, feet	Fourth 6 inches, feet	Maximum, feet	First 6 inches, feet	Second 6 inches, feet	Third 6 inches, feet	Fourth 6 inches, feet
Aitkin		12	200	5.0	0.30				0.30	0.34			0.34	0.23
	Sandy	10	295	4.5	0.18		0.17	0.15	0.15	0.17		0.17	0.15	0.15
	loam	12	600	4.0	0.18	0.10	0.10	0.10	0.10	General rise				
		10	800	5.0	0.18	0.07	0.07	0.07	0.07	General rise				
Meadowlands		27	60	3.4	0.80			0.67	0.55	1.05		0.62	0.53	0.38
	Silt	27	90	3.4	0.80		0.71	0.50	0.41	0.70		0.48	0.40	0.29
	loam	27	135	3.4	0.75	0.75	0.55	0.38	0.31	0.65	0.45	0.36	0.30	0.22
Paynesville	Loam	21	100	4.0	0.74			0.64	0.50	1.10		1.10	0.45	0.38
		21	250	4.2	1.02	0.69	0.58	0.35	0.23	0.55		0.55	0.24	0.20
Waseca	Clay	35	45	3.4	2.90	2.04	1.00	0.70	0.60					
		30	125	3.6	1.80	1.06	0.54	0.38	0.31					

The average rate of drop of the ground water is an exponential function of the hydraulic slope (see Fig. 22). The equation for the rate of drop was determined graphically to be of the following form:

$$R_d = 0.165\ S^{3/4} \qquad (2)$$

R_d is the rate of drop mid-way between tile lines in feet per day. S is the hydraulic slope expressed as feet of head of the ground water surface above the tile per 100 feet distance from the tile lines.

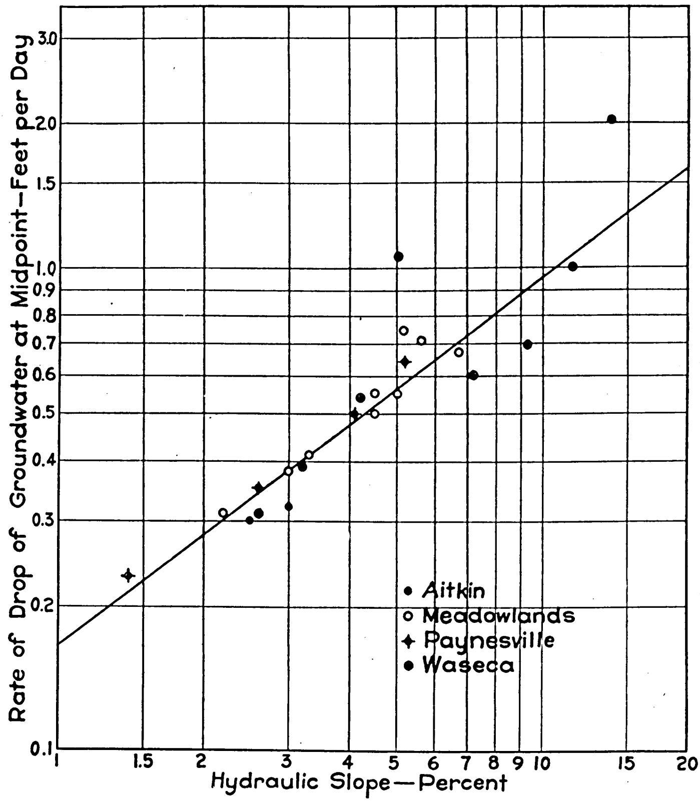

Fig. 22. Relation of the Rate of Drop of Ground Water at Mid-Point Between Tile Lines to the Hydraulic Slope

This equation is an average and is not likely to be followed very closely in the downward movement following any given rain. Nevertheless, it may often serve as a guide in design for a given locality where rate of drop is an especially important governing condition.

Relation of rate of drop at mid-point to the tile spacing.—The slope which the ground water takes is determined largely by the texture of the soil and the spacing of the tile lines. For uniform soil conditions, the rate of drop of the ground water table at the mid-point between tile lines is an exponential function of the tile spacing of the following form: (See Fig. 23.)

$$R_d = K(T_s)^{-0.7} \qquad (3)$$

R_d is the rate of drop as in Equation 2. K is a drainage factor depending upon the hydraulic slope and the type of soil. T_s is the tile spacing in feet.

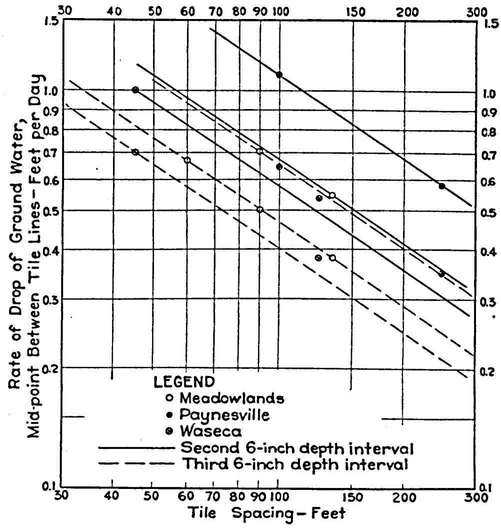

Fig. 23. Relation of the Rate of Drop of Ground Water at Mid-Point Between Tile Lines to the Spacing of the Tile Lines

As the value desired in practice is that of tile spacing rather than rate of drop of the peak of the water table between the tile lines, we may solve Equation 3 for T_s as shown in the following equation:

$$T_s = \left(\frac{K}{R_d}\right)^{1.43} \qquad (4)$$

As K is a factor depending upon the hydraulic slope and the type of soil, its value can be measured by the moisture equivalent when a definite slope is considered.

K may be obtained graphically by plotting the rate of drop of the ground water through a known depth interval of a particular soil type as the ordinate and tile spacing in feet as the abscissa. Then K is the value of R_d when T_s is unity. It varies directly with the hydraulic slope and inversely with the moisture equivalent. (See Table 16 and Fig. 24 for values of K.) The Meadowlands soil, being the most uniform of the four stations, shows the most consistent relationship. As the soil was the most uniform and as there were three different spacings of tile lines, the rates of drop of the ground water at the Meadowlands station

Table 16
Values of "K" (Drainage Factor or Value of R_d When $T_s = 1$) Corresponding to Different Soil Characteristics

Moisture equivalent	Plastic limits		Clay, per cent	K
	Lower	Upper		
10	7.0	12	12.5	53.5
15	10.5	18	18.7	34.0
20	14.0	24	25.0	24.5
25	17.5	30	31.2	19.4
30	21.0	36	37.5	16.0
35	24.5	42	43.7	13.2
40	28.0	48	50.0	11.5

were taken as a basis for establishing the slope of the logarithmic graphs of the exponential functions. The rates of drop through any depth increment for the different tile spacings fall on a line with a negative slope of approximately 0.7. The logarithmic graphs for the rates of drop at the other stations were constructed parallel to the ones for the Meadowlands station. (See Fig. 23.) Those for Paynesville check closely, but those for Waseca do not check, evidently owing to the difference in texture of the Waseca soil. The average moisture equivalent of the Waseca soil where the tile lines are spaced 45 feet is 35, while the average moisture equivalent is 30 where the tile lines are spaced 125 feet. At Aitkin, as the ground water did not come within the second 6-inch depth interval and was within the third 6-inch depth interval only once for the most effective spacing, there were no comparative values to plot.

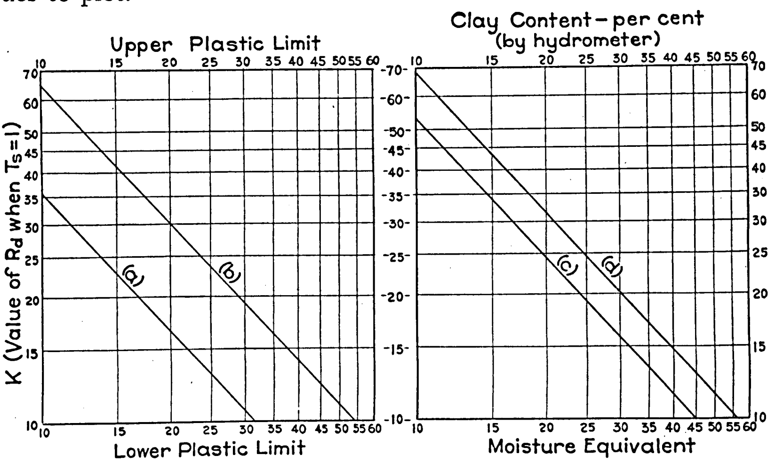

Fig. 24. Relation of "K" (Drainage Factor) to Four Soil Characteristics: (a) Lower Plastic Limit, (b) Upper Plastic Limit, (c) Moisture Equivalent, (d) Clay Content

With the limited observations made, it was found that the crops were not seriously injured if the water table was held at least 6 inches below the surface and was lowered at the rate of one foot per day through the second 6-inch depth interval and at the rate of 0.7 foot per day through the third 6-inch depth interval. Moreover, if the tile spacing required to give a rate of drop of one foot per day through the second 6-inch depth interval, or 0.7 foot per day through the third 6-inch depth interval, is plotted as ordinate and the moisture equivalent as abscissa (see Fig. 25), a graph is obtained giving the tile spacing necessary for the optimum rate of drop for any soil type.

The equation of this graph is:

$$T_s = \frac{12{,}000}{(M_e)^{1.6}} \qquad (5)$$

T_s is the tile spacing in feet and M_e is the moisture equivalent.

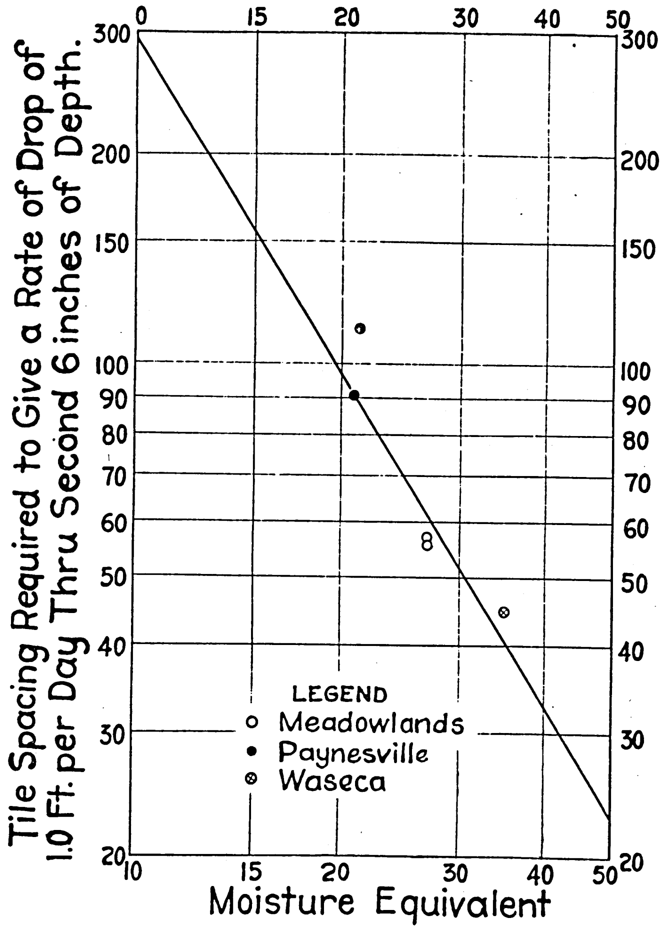

Fig. 25. Tile Spacing Required to Lower the Ground Water a Definite Amount Per Day

Direct relation of the moisture equivalent to tile spacing and depth.—Practically the same formula as that given in Equation 5 may be obtained by considering the effectiveness of the drainage system and the porosity of the soil as represented by the moisture equivalent.

In order that the water may get to the tile lines, there must be lateral as well as vertical movement. This lateral movement is caused by the "head" of water from the tile line to the mid-point. Under average conditions the spacing of the tile lines should be such that the maximum "head" of water would be at least one foot below the surface. Since the gravity water moves at any appreciable rate only through the non-capillary pores, the larger the pores the more rapid the movement of the water. Therefore the spacing and depth of any tile system is a function of the non-capillary pore space of the soil. But since the pore space is a function of the moisture equivalent (11), it is reasonable to expect the spacing and depth of the tile lines also to be a function of the moisture equivalent, which is determined much more easily than the pore space.

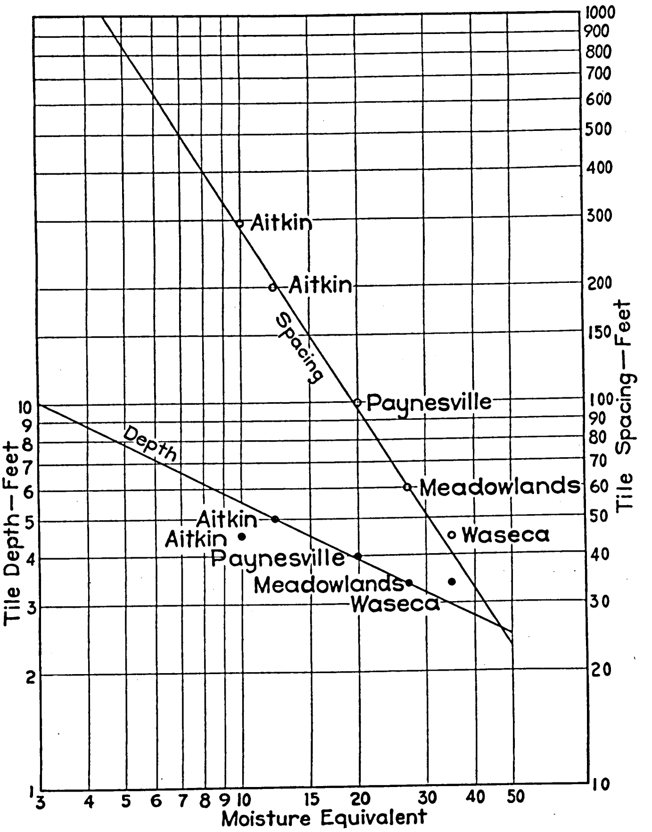

Fig. 26. Tile Spacing and Depth with Respect to the Moisture Equivalent

The most effective spacing and depth of tile lines for each station observed were plotted as ordinate and the moisture equivalent as abscissa on logarithmic graph paper. The points lie in fairly straight lines. (See Fig. 26.) The equations of the lines are:

$$T_s = \frac{10{,}000}{(M_e)^{1.55}} \tag{6}$$

$$T_d = \frac{17.5}{(M_e)^{0.5}} \tag{7}$$

T_s = tile spacing in feet. T_d = tile depth in feet. M_e = moisture equivalent.

The two methods given in Equations 5 and 6 will give tile spacings that show maximum differences of only a few feet. For tile spacings up to 100 feet, the differences vary from 0 to 3 per cent, the difference increasing with the spacing.

The depth at which the tile was actually laid at Aitkin was the same for the 300- as for the 200-foot spacings. It was impossible to get the tile any deeper owing to the shallowness of the outlet.

From Equations 6 and 7, a nomograph (Fig. 27) was worked out giving the spacing and depth of tile lines for any given moisture equivalent. This nomograph was made in the form of an equilateral triangle in the following manner: A complete moisture-equivalent scale

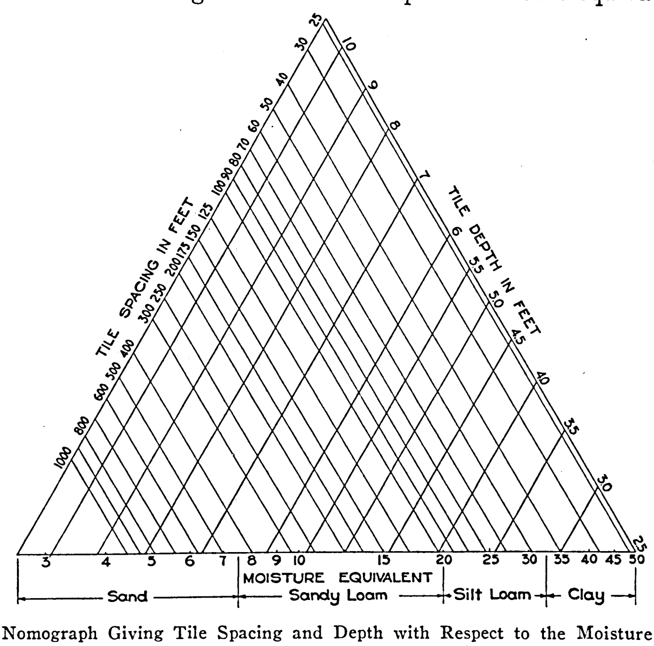

Fig. 27. Nomograph Giving Tile Spacing and Depth with Respect to the Moisture Equivalent

was established along the base of the triangle using logarithmic units because the spacing and depth are both exponential functions of the moisture equivalent.

For definite tile spacings, such as 25, 40, 100, 200, or 1,000 feet, the corresponding moisture equivalents were read from Figure 26. These values were spotted on the moisture equivalent scale on the base of the triangle and through the points thus established lines parallel to one leg were drawn intersecting the other leg. These intersections were marked respectively to indicate the spacings originally selected, thus establishing along this leg of the triangle a logarithmic tile-spacing scale.

In a similar manner the depth scale was established along the other leg.

Examples illustrating the use of Figure 27.—For example, if it is desired to determine the proper spacing and depth of tile lines in a soil whose average moisture equivalent is known to be 20, take the following steps: (a) Locate the moisture equivalent on the horizontal scale. (b) Follow the 60-degree diagonal line to the left—or parallel to this line in case of some other value of moisture equivalent not on a diagonal line—to the intersection of the tile-spacing scale, thus getting the proper tile spacing for this soil type, in this case about 100 feet. (c) From the point on the moisture-equivalent scale located in (a), follow the 60-degree diagonal line to the right—or parallel to it as in (b)—to the intersection of the tile-depth scale, thus getting the depth for this soil type, in this case about 4.0 feet. If the moisture equivalent is 35, the spacing should be about 40 feet and the depth 3.0 feet.

Where outlet conditions are poor and the proper depth cannot be obtained, the spacing should be for the moisture equivalent **corresponding to the depth obtainable.** If, in the first case mentioned, the maximum depth obtainable was 3.5 feet, which corresponds to a moisture equivalent of 25, the spacing should be about 70 feet instead of 100 feet.

Relation of Soil Plasticity and Clay Content to Tile Spacing and Depth

Since it is not usually possible for practising drainage engineers to determine moisture equivalents, the writer has worked out a relationship between moisture equivalent and the soil plasticity, and between moisture equivalent and clay content. (See pages 13 to 16 and Table 3.) These relationships being established, he has also worked out nomographs giving the spacing and depth of tile lines with respect to these two physical properties. Since it was found that the plasticity or clay content of the soil is a definite percentage of the moisture equivalent, the scale for plasticity or clay content was substituted for that of the moisture-equivalent scale. The scales of tile spacing and depth were left the same as developed for the moisture-equivalent scale and as shown in Figure 27. (See Figs. 28 and 29.)

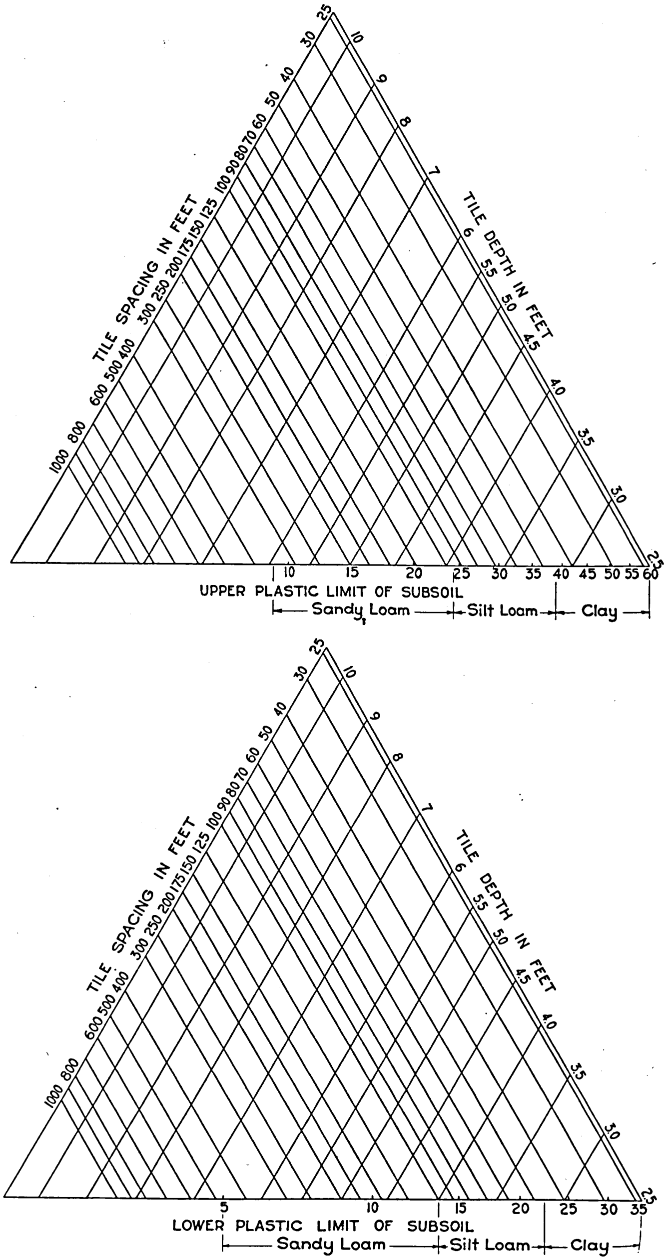

Fig. 28. Nomographs Giving Tile Spacing and Depth with Respect to the Soil Plasticity

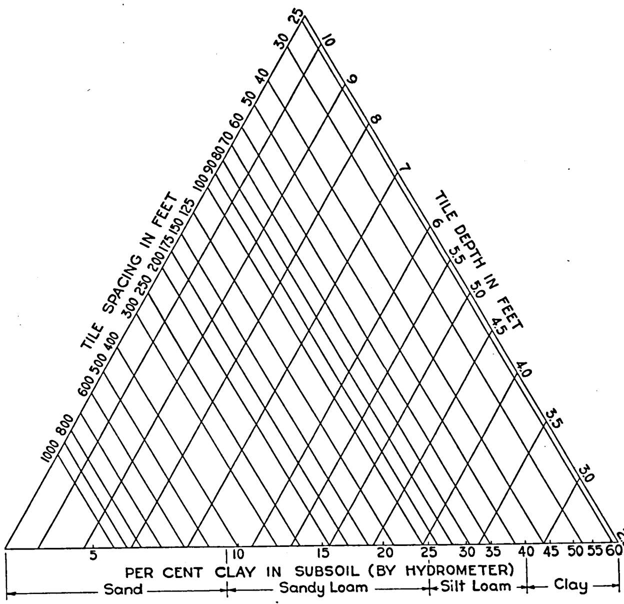

Fig. 29. Nomograph Giving Tile Spacing and Depth with Respect to the Per Cent of Clay in the Subsoil

Since the plasticity cannot be determined on the sandy soils (those with a moisture equivalent below 15 to 20), it is necessary to use some other characteristic to determine the tile spacing and depth for these soils. The percentage of clay by the hydrometer method, as developed by Bouyoucus, was used in this study and found to be a fairly reliable method.

After determining the soil plasticity or the percentage of clay, by the methods outlined on pages 13 to 16, the proper spacing and depth of tile drains is determined by means of the nomographs in the same manner as illustrated for the moisture equivalent. (See Figs. 28 and 29.)

These graphs are worked out for a maximum annual rainfall of 30 inches and a maximum monthly rainfall of 6 to 9 inches. The greatest 24-hour rainfall occurring during this study was 3.80 inches at Waseca on August 1, 1928. In localities where greater or lesser rainfall intensities are encountered, additional tests should be made to supplement.

Procedure for Variable Rates of Drop of the Ground Water

In the foregoing discussion there was assumed an optimum rate of drop of one foot per day for the ground water at the mid-point between the tile lines. Under certain crop rotations it may be desirable to use some other rate of drop. For such cases the proper tile spacing for rates of drop ranging from 0.2 to 2.0 feet per day may be obtained from Figure 30 as illustrated by the example under the figure.

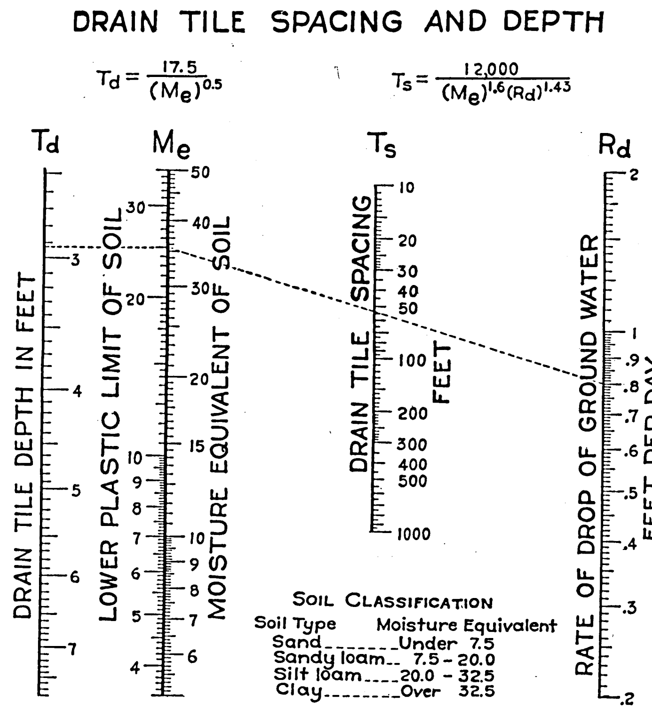

Fig. 30. Nomograph Giving Tile Spacing and Depth for Variable Rates of Drop of the Ground Water

Example: Required to determine the tile spacing and depth necessary to give an average rate of drop at midpoint between tile lines of 0.8 ft. per day for a soil whose average plasticity is 25 (moisture equivalent, 35.7).

Solution: A straight line between 25 on the plasticity scale (M_e) and 0.8 on the rate of drop scale will give the proper spacing where it crosses the tile spacing scale—in this case 54 ft. The proper corresponding depth is the reading on the tile depth scale directly across, horizontally, from 25 on the plasticity scale (M_e)—in this case 2.9. If, in the case just mentioned, the desired rate of drop is 1.2 ft. per day, the spacing would be 29 ft. with the depth the same as before.

SUMMARY

In northern latitudes where the ground remains frozen all winter the winter precipitation can usually be disregarded as far as the design of the tile system is concerned, because the snow melts in the spring and runs off over the surface before the ground thaws.

About one-half of the rainfall from March 1 to October 31 occurs in rains of less than one inch, one-fourth in rains of 1.00-1.99 inches, and one-fourth in rains of 2.00 inches or more. In terms of the number of storms, less than one inch falls during 82 per cent of the storms; 1.00 to 1.99 inches fall during 12 per cent, and 2.00 inches or more fall during 6 per cent of the storms. As there is an average of 30 storms per season (March 1 to October 31), there would be an average of less than 2 storms per year when 2.00 inches or more fell in 24 hours.

Little or no flow occurs through the tile drains after a rain if there has been less than 3 inches of rain in the previous month. Practically all rains of more than one inch when preceded by 3 inches or more in the previous month cause run-off. Rains of less than one inch occurring during the growing season (May 1 to August 31) are not likely to cause run-off through tile lines, unless they are preceded by 4 inches or more during the previous month.

As a general rule, the percentage of run-off is less for the larger than for the smaller rains which cause run-off, and is less during the growing season than for early and late rains, since the growing crops exert a noticeable influence upon the amount of run-off.

The maximum run-off usually occurs during the first 6 hours after the heavy part of the storm and may exceed a rate of one acre-inch per day if the system will carry it. Where there are surface inlets to the tile line, the time of concentration is less than 6 hours.

Following a dry period of 2 to 4 weeks during the growing season, it takes several inches of rain to bring the soil to its maximum capillary capacity. Until this point is reached, there will be no fluctuation of the water table and **consequently no action by a tile drainage system.** After the capillary capacity is reached, the ground water table rises rapidly during a storm, but subsides very much more slowly, the rate of drop being an exponential function of both the hydraulic slope and the tile spacing. (See Equations 2 and 3.)

The rate of drop is much faster during the growing season than for early spring and late fall rains, owing to the combined action of heavy transpiration and tile drainage when it exists.

The proper spacing and depth of tile lines is dependent upon three important factors: (a) the type of soil, (b) the types of crops grown,

(c) the climatic conditions. The observations made by the writer indicate that the crops were not seriously injured if the water table was held at least 6 inches below the surface and was lowered at the rate of one foot per day through the second 6-inch depth interval and at the rate of 0.7 foot per day through the third 6-inch depth interval.

Spacing and depth of tile lines is an exponential function of some physical property of the soil as, for example, (a) the moisture equivalent, (b) the plasticity, and (c) the percentage of clay. This functional relationship to the moisture equivalent is shown in Equations 5, 6, and 7. It is shown graphically in Figures 26 to 30, inclusive, for each of the three properties just named for use in tile drainage design.

CONCLUSIONS

It seems clear to the writer that the data included in this study and the analysis herein presented strongly support the following statements:

(a) Neither intense nor long-continued rainfall are in themselves alone a reliable index of needed capacity in a drainage system.

(b) Heavy subsurface run-off, even when a good outlet is available, does not necessarily follow closely on heavy rainfall. Rather it is dependent on the texture of the soil and sub-soil, the soil moisture content preceding the rainfall of which the run-off is a final consequence, and the period of the year relative to plant growth.

(c) The proper determination of the maximum required effectiveness of a tile drainage system should generally be based on soil moisture and run-off conditions present during the early weeks of the growing period.

(d) The effectiveness of a tile drainage system as a protection for, and a stimulant of, crop growth is manifestly dependent on the rate of drop of the water table at the mid-point between the drains. This rate of drop is dependent on the texture and moisture condition of the soil when well drained and on the depth and spacing of the tile drains, and it is clearly shown in this discussion that both rate of drop and depth and spacing of tile drains are definite functions of the moisture equivalent, the plasticity, or the clay content of the soil under consideration.

(e) Before the method of tile drainage design herein presented can be considered complete, it is probable that these equations should be checked under a wider variety of soil and climatic conditions. Furthermore, without question, the rate at which the water table should be lowered to avoid injury to plant growth should be determined by definite research, because, altho a rate of drop of one foot per day through the second 6-inch depth interval is considered desirable, this rate was obtained by the writer from general observations rather than from actual determinations of plant growth and yields.

(f) Nevertheless, the results obtained by Equations 4, 5, 6, and 7 give tile spacings and depths closely comparable to those recommended by other American investigators, as nearly as can be determined from the general classification of the soils included in their studies.

(g) The method proposed by the writer has the following decided advantages over any other thus far proposed: 1. It is readily applicable by any engineer as it does not call for intricate tests requiring expensive special equipment difficult to secure. 2. Results obtained by the use of these formulas in any locality can be intelligently compared with, and definitely checked against, results obtained by the same method in any other locality.

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